GEOPHYSICS

VOL. XXVI, NO. 2 APRIL, 1961

Presidential Address—Is There a Future for Geophysics? ..... *T. O. Hall* 133

Interpretation of Synthetic Seismograms ..... *R. L. Sengbush, P. L. Lawrence and F. J. McDonal* 138

Underground and Surface Gravity Survey, Leadwood, Missouri ..... *S. T. Algermissen* 158

Some Aspects of Elastic Wave Propagation In Fluid-Saturated Porous Solids ..... *J. Geertsma and D. C. Smit* 169

Quantitative Interpretation of Gamma-Ray Logs ..... *J. H. Scott, P. H. Dodd, R. F. Droullard, and P. J. Mudra* 182

Propagation Effects in Induction Logging ..... *W. C. Duesterhoeft, Jr.* 192

Induced Polarization in Electrolyte Saturated Earth Plugs ..... *J. H. Henkel and T. C. Collins* 205

The Diurnal Problem in Aeromagnetic Surveying in Canada ..... *K. Whitham and E. R. Niblett* 211

A Simple Integral Transform and its Applications to Some Problems in Geophysical Interpretation ..... *A. Roy and S. Jain* 229

DEPARTMENTS

Discussions and Communications

Water Reverberations—Their Nature and Elimination ..... *F. Kalisvaart and A. J. Seriff* 242

Reviews 243

Publications Received 248

Patents 249

Contributors 255

Membership Applications Received 259

Nominees for the 1961-62 Executive Committee 261

Announcements 266

Abstracts

Bulletin (Izvestiya) 267

Geophysical Prospecting 272

Personal Items 274

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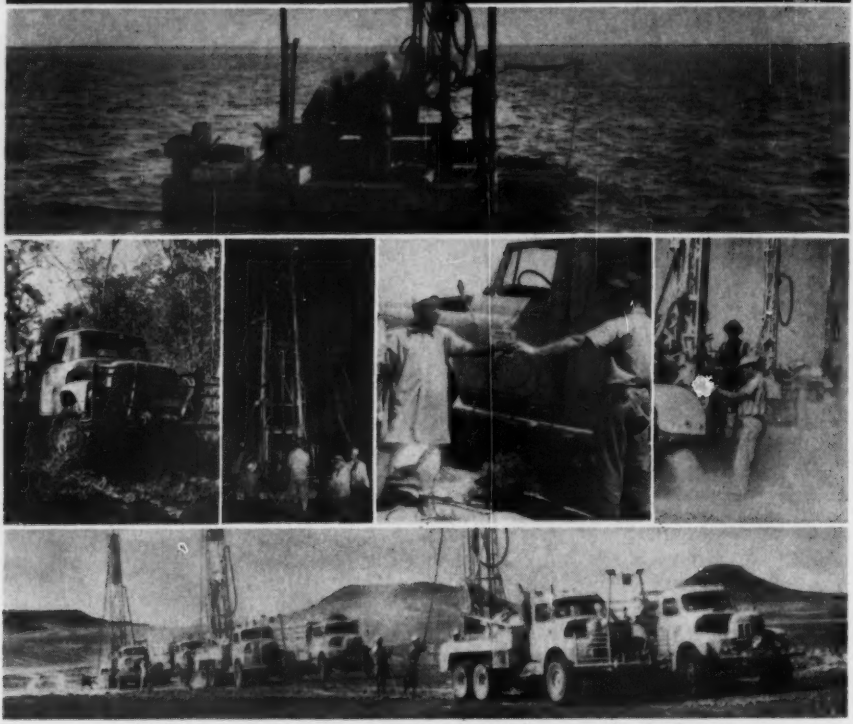

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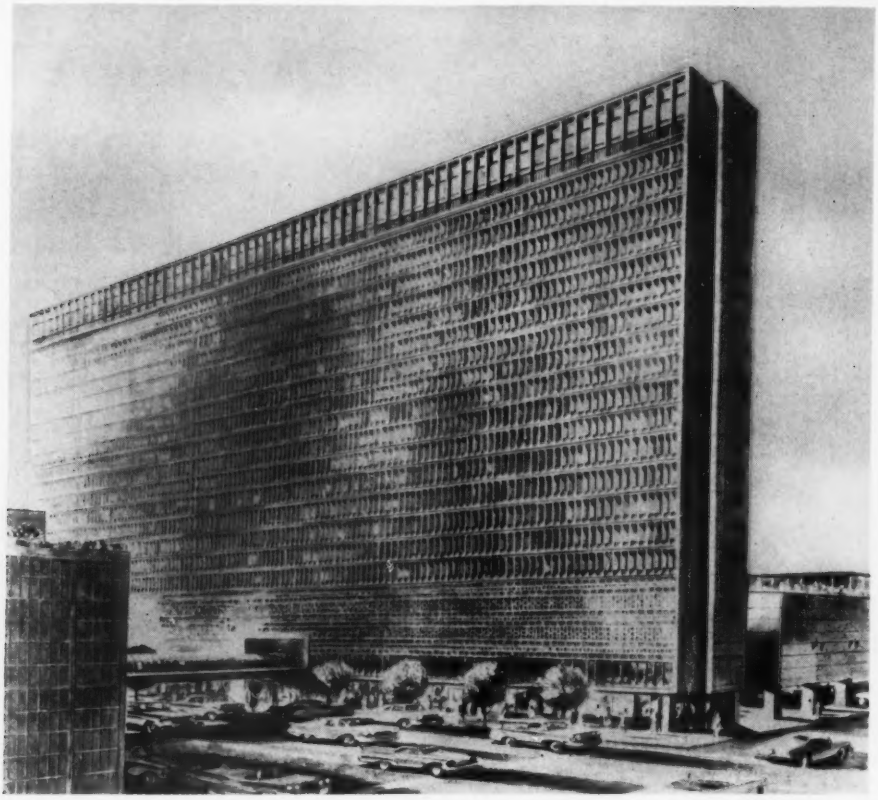

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22	4	October	1957
22	Yearbook	December	1957
23	1	January	1958
23	2	April	1958
23	3	July	1958
23	4	October	1958
23	5	December	1958
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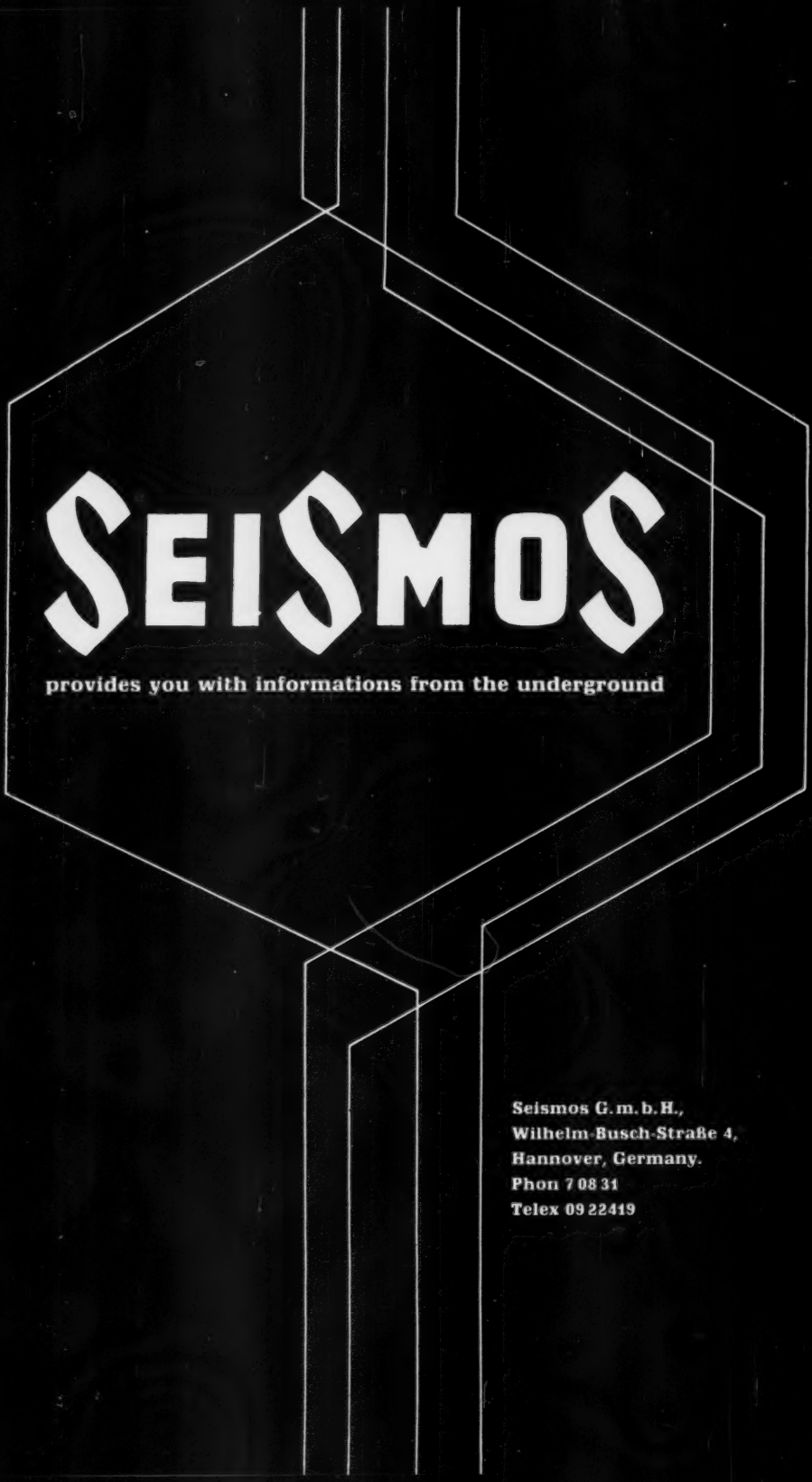

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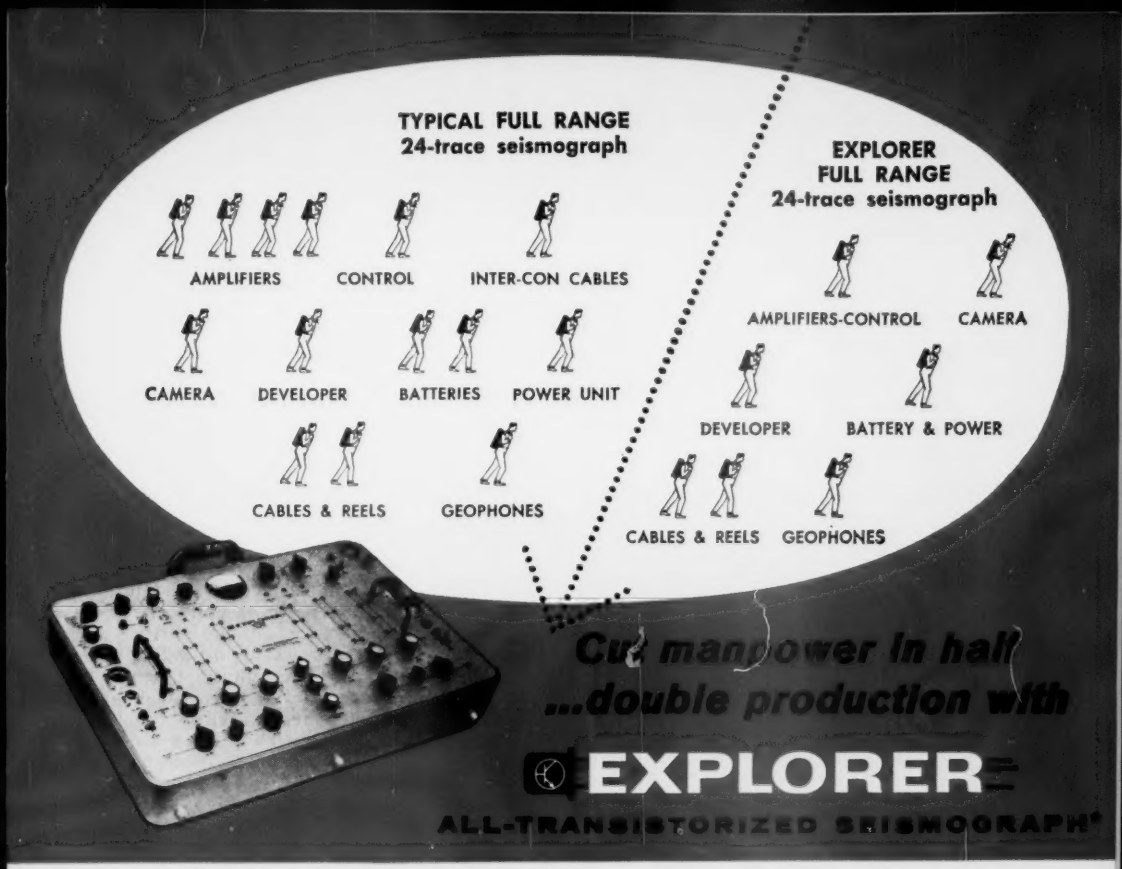

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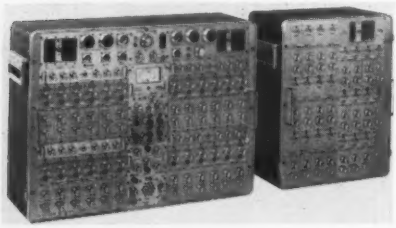

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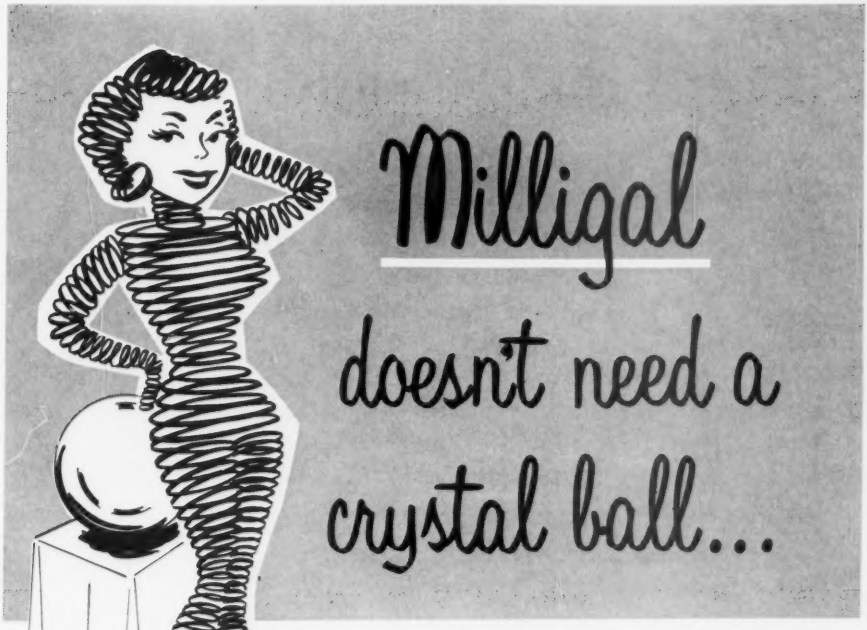

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Compagnie Generale de Geophysique 36–37
Continental Geophysical Co. 42

Bert & Ralph Duesing 46
Du Pont-Photo Products 39

Eastman Kodak Co. 64
Electrodynamic Instrument Corp. .....
..... 41, 43, 45, 47, 48–49
Electro-Technical Labs 33–34
Exploration Products 65

Fairchild 62

General Geophysical Co. 69
Geophysical Associates Int'l 16
Geophysical Service Inc. ..... 4th cover
Griffin Tank & Welding 66

Hall-Sears, Inc. 70
Hawthorne 27
Hunting 59

Industrial Photographers 58

Marine Geophysical Services 44

E. V. McCollum & Co. 11
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Mayhew Supply Co., Inc. 50
Minnesota Mining & Mfg. Co. 38

National Geophysical Co., Inc. ..2nd cover

Petty Geophysical Engineering Co. 35
PRAKLA 57

Rayflex 24
Robert H. Ray 63
Rogers Geophysical Companies 67

Schlumberger Well Surveying Corp. .. 55
Seismic Explorations, Inc. 40
Seismograph Service Corp. .....3rd cover
Seismos GmbH 8
Society of Petroleum Engineers 56
Southwestern Industrial Electronics ..51–54
State Boat Corporation 65

Texas Instruments, Inc. 9
Texas Seismograph Co., Inc. 37
Tidelands Exploration Co. 26

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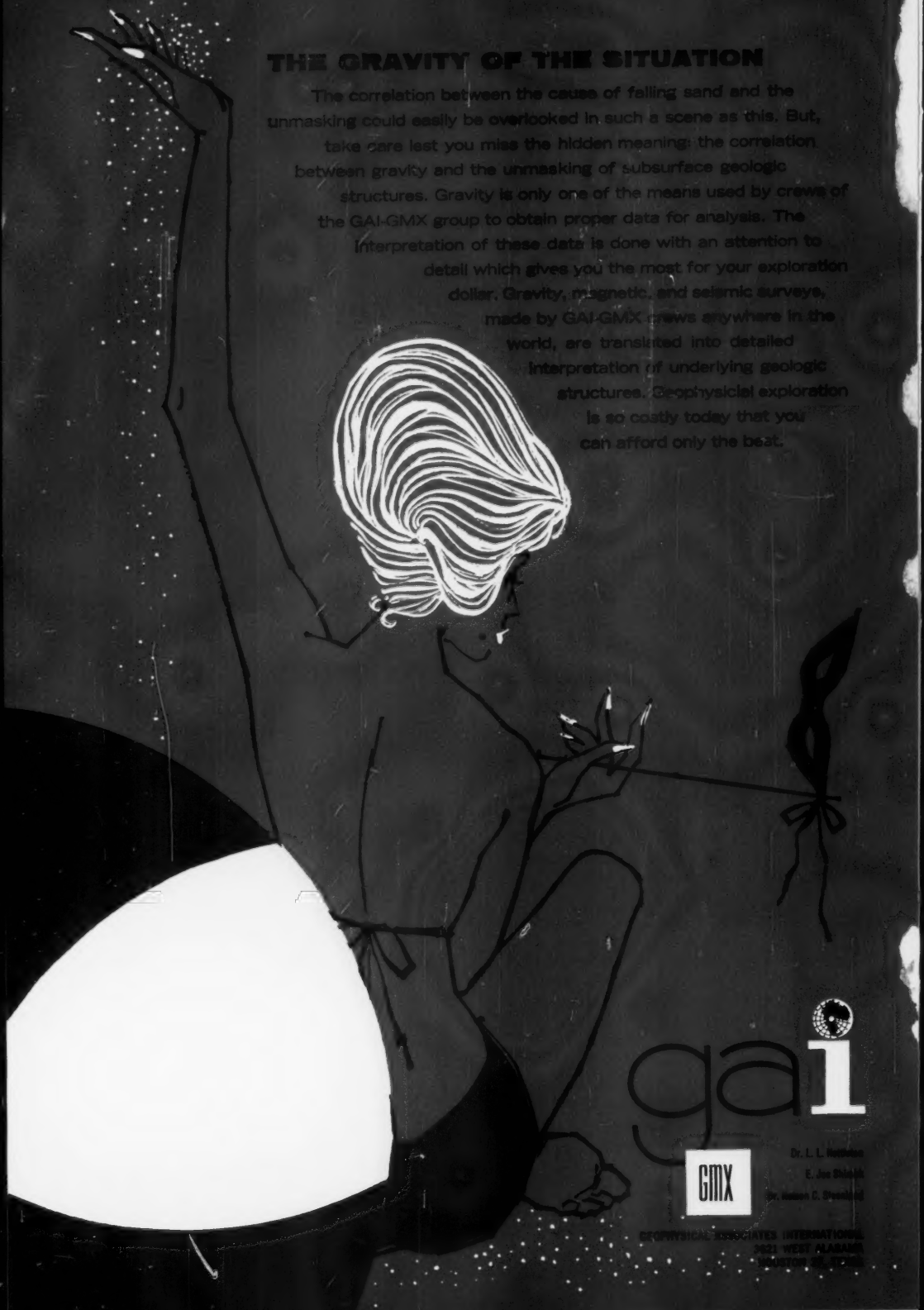

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VOLUME XXVI APRIL, 1961 NUMBER 2

GEOPHYSICS

PRESIDENTIAL ADDRESS

IS THERE A FUTURE NEED FOR GEOPHYSICS?*

T. O. HALL†

If there is a future need or demand for geophysics, and we are concerned primarily with exploration geophysics, it follows that there surely must be a future for exploration geophysics, providing this industry stays modern, efficient, and competitive.

At the April meeting of the American Association of Petroleum Geologists in Atlantic City, I gave some figures, which were estimates of the future need for reserves of oil and gas for the U. S. and for the free world. These estimates were based on the forecasts of various domestic and international organizations. The statistical data will not be presented here, since it has been published in the Bulletin of the American Association of Petroleum Geologists. It is interesting, however, to note that Sir Stephen Gibson, Permanent Chairman of the World Petroleum Congress and Director of Iraq Petroleum Company, produced a comparable set of figures in Atlantic City recently, and some of his predictions will be reviewed here. He said that in 20 years the present 275 billion barrels of oil reserves will be consumed and that at *least* an equal amount will have to be found during this period of time.

Sir Stephen predicted that by 1980 world demand will be between 18 and 20 billion barrels annually. This means that if we only replace the 275 billion barrels depleted by 1980, we would only have 15 years supply at that time. In other words, to maintain an efficient rate of production *much more* than 275 billion barrels will have to be found in the next 20 years.

It has been estimated that this country will need 14.2 million barrels of oil daily by 1970. This is based on an annual growth rate of 4 percent. If this is reasonable, it will be necessary for the exploration industry to find 52 billion barrels of additional reserves in the U. S. by 1970 if we are to maintain a safe domestic reserve position. This compares with 35.5 billion barrels of oil found in this country in the 1950's.

Sir Stephen also made another very encouraging statement at Atlantic City. He said that the present world oil surplus will not last more than two or three years. This is, of course, contrary to the several outstanding seers in the industry who have said that an oil surplus would be with us for at least ten years. However, his thinking is borne out by a recent World Petroleum release stating that "Views of these industry leaders will surprise a good many of the pessimists. The amazing 15 percent rise in European consumption during the first quarter of this year and the strong demand in other world areas was much greater than hoped, with the result that there is less dismay among oil management than among the pundits." Furthermore the daily average consumption in the free world increased 6.5 percent to 20.5 million barrels in 1959, and the market in Italy has increased 27 percent this year alone, with an increase of 11 percent indicated for all Western Eu-

* Presented at the 30th Annual Meeting of the Society of Exploration Geophysicists, Galveston, November 7, 1960.
† General Geophysical, Houston, Texas.

rope. In addition the fast developing countries of Africa, Asia, and Latin America are huge potential markets for petroleum.

Sir Stephen made another significant statement. He said that he did not believe that the Middle East, where most of the world's present reserves are located, would provide more than 75 billion of the 275 billion barrels, *plus*, new reserves that must be found in the next 20 years. This means that the exploration industry must turn to areas not intensely prospected outside the Middle East to develop these huge reserves.

The use of natural gas has grown at a fantastic rate in recent years. World Oil recently stated that marketed production of Texas and Louisiana gas alone had increased 246 percent from 1946 to 1959. Based on the American Gas Association forecasts of U. S. consumption this trade journal predicts that by 1964 the States of Texas and Louisiana alone will have to be adding gas reserves at a rate of between 17.7 and 21.0 trillion cubic feet annually. The new reserves developed during the period of 1955–1959 were at an annual rate of 15.3 trillion cubic feet annually, consequently those two states, which developed approximately 61 percent of the new domestic reserves in recent years, must increase their annual level of new discoveries, extensions and revisions by about 38 percent to meet the requirements of local and interstate natural gas markets.

The Chase Manhattan Bank of New York City concurs in the need for the development of large new gas reserves. It has stated recently that the exploration industry must find 300 trillion cubic feet of new gas by 1970, and we have found only 181 trillion in the past 10 years.

Certainly in the United States the new reserves of oil and gas that are needed for the future will not be easy to find. A large portion of them must come from the areas which are difficult to prospect; areas where the geology is covered by sand, limestone, volcanics, marsh or water, or in highly inaccessible areas. This is the type of prospecting that lends itself to the use of geophysical tools.

Even in the foreign countries where we may expect to find large additional reserves, the use of geophysics is almost mandatory. In Northern Canada much of the prospective area is covered by glacial formations and muskeg. In Africa large sections are covered by sand, loose rocks, jungle vegetation, marshes, etc. We find the same story wherever we go to look for additional reserves. The fact that wildcats drilled in remote and foreign areas are so terrifically expensive makes it imperative that they be located on the best information possible.

From the preceding facts we can see there is and will be a need for an effective oil and gas finding tool. The question then is; is geophysics an effective tool for this purpose? Recent statistical data show that for the three-year period, 1957–1959, approximately 16 percent of the new field wildcats located in the U. S. on the basis of geophysics alone were successful. This percentage would undoubtedly be higher if lease ownership conditions did not play an undue influence in locating many of these wildcats. These same statistics show that the same success ratio results when a combination of geophysics and geology is the basis for the location of new field wildcats. Thus, we can see that geophysics is still an effective exploration tool in the U. S., and that a much higher success ratio could be expected in areas that have not been so intensely prospected as the U. S. As a matter of fact, a large part of the crude reserves of the world today attest to the effectiveness of geophysics as an exploration tool.

There is a future need for geophysics, and geophysics is still an effective exploration tool, but we in this industry cannot afford to be complacent. Under present market conditions, the geophysical costs for finding oil in the U. S. are too high. This is not because the geophysicists are paid too much or the geophysical contractors are paid too much. Quite the opposite is true. It is a well-known axiom that *you always get what you pay for*. Well-paid men deliver more than underpaid ones.

Three avenues are open to the geophysical operator who intends to produce, at competitive prices, the future reserves needed by this country and the free world. First, he must reduce operating costs; second, he must continuously develop effective new tools and techniques; third, he must radically improve the interpretative methods by making better use of the geophysical data obtained by field parties.

Much has been accomplished in attaining the first two of these objectives. Efficient personnel produce more per work-day, and they plan and develop many ingenious field short cuts. Further savings are realized by such innovations as

cheaper explosives, twin recording units, two and three meter teams out of a common camp for overseas gravity jobs, and improved transportation means. There has been a steady development of new tools and techniques, pattern holes, multiple geophone arrays, improved recording instruments, magnetic recording with its many applications, weight-dropping techniques, continuous velocity log, and directional shooting to mention only part of the recent developments.

I am not so sure that we have done as well in the field of improved interpretation. Interpretation is an area where geology and geophysics are inseparable, because the final objective of all geophysical exploration is an interpretation in geological terms.

The geophysical interpreter should not be completely dependent upon any geologist for his understanding of geology in general or the geology of the local region in which he is working. This is true, because of the poor communication of ideas between people of different scientific backgrounds and different thinking patterns, and also because there is always the danger of a breakdown in liaison between geologist and geophysicist. This could be due to an unworkable chain of command, a succession of personnel changes, or other extraneous reasons. Furthermore, it is extremely important that the geophysicist have the full confidence of the geologists with whom he is in contact; this confidence will be destroyed—perhaps beyond remedy—to the detriment of the entire science of geophysics, if geophysicists present interpretations that are geologically impossible or improbable.

To achieve and merit the status of full partners in exploration, our interpreters must become fully versed in the application of geological information to magnetic, gravimetric and seismic data. First, they must be or become grounded in the fundamentals of geology. From a grasp of the principles of basic geology they must proceed to the geology of the broad region to which they are assigned, and finally to a detailed understanding of the geology applicable to the specific and perhaps limited area to which they are assigned.

To become the top-flight geophysical interpreter which we must have to stay competitive in the exploration field, this individual must know and understand the geological aspects which we have discussed, but he must have an even more thorough grasp of his geophysical specialty. At the same time, he needs more than a casual understanding of the other geophysical methods. In fact, he must be a well-rounded geophysicist before he can interpret geophysical data in geological terms.

No interpreter can do the job demanded of him unless he makes full use of the data obtained by his crew or his company. He must examine in detail every bit of evidence, in the light of the latest and best ideas developed through research. This examination must be made with an inquiring, imaginative attitude; new interpretive and computing techniques frequently must be developed to solve specific problems. Naturally, experience will be invaluable in the development of new interpretation techniques and ideas; consequently, a good interpreter will profit by his senior's experience. To summarize, a top-flight geophysical interpreter must be well qualified in all phases of geophysics, a competent geologist, and a man with drive and imagination.

Actually there is a fourth avenue which we in the geophysical industry must follow in order to produce the future reserves of oil and gas. This fourth avenue vitally effects all three of the other avenues that have been mentioned previously. This avenue is the one of research. There is a widespread opinion that the geophysicists have reached the end of the road in the development of geophysical tools, that they know all there is to know about the very basic phenomena concerned with geophysics. Nothing could be further from the truth. Geophysics is essentially no different from any other science. The more you learn, the more you realize how much you do not know, and the more avenues for development, study and additional research are opened.

To exemplify why I believe that research will lead us to new, useful, and probably unforeseen avenues, let me discuss briefly a few topics of seismology that seem to require a great deal of additional study.

Basic to the improvement of the seismic method is recognition that seismic waves are the most complicated waves of all those studied in physics; while sound in a gas or liquid is described by a single longitudinal, or pressure wave, and while electro-magnetic waves require a vector-wave description because of their transverse character, seismic waves in solids have *both* longitudinal and

transverse waves. In spite of this known complexity, the exploration seismologist has had considerable success by utilizing only the simple pressure wave aspect of the seismic waves and he has usually ignored the existence of other types of motion unless surface wave and shear wave noises have forced their consideration. This situation clearly needs improvement. In many cases these modes do not really constitute "noise" but are really a part of the signal that could, with improved instruments and understanding, yield additional and valuable information.

Basic research seems needed for a complete understanding of the different modes of seismic wave propagation. For example, how does the type of source (explosion, patterned shots, thumper, etc.) effect the generation of different modes? How does the nature of the earth—its layering, and inhomogeneities—effect the conversion of one mode into others? There is a simple but unanswered instrumentation question involved in such considerations: how can one, in practical field observations, distinguish between different modes of motion?

Thus, it seems reasonable to expect an improvement of seismic information if one knew how to detect and interpret the different modes of seismic vibration.

Another subject that is poorly understood is the frequency spectrum of seismic waves. There are many mechanisms, such as true friction, and scattering in layered media that may explain the removal of high frequencies from a seismogram. Why, then, does the typical seismogram have a rather narrow band of frequencies with few low frequencies present? This phenomenon certainly has to do with the nature of the seismic source but more work is needed to understand it. Again there is the expectation that any improvement of basic understanding will have practical consequences; for example, the problem of the identification of pinch-outs and lenses is intimately connected with the frequency spectrum of the seismic waves.

The seismic method certainly does not detect oil but rather conditions favorable for oil accumulation. However, a seismogram contains more information than the refraction and reflection "picks." Indeed, the exact forms of seismograms —all the wiggles and phases and the absolute amplitudes—contain information about the earth that is usually ignored. It should be possible to construct the pressure wave and shear wave velocity *versus* depth from seismograms; it should be possible to construct the accoustic impedance, or the density, or Young's modulus *versus* depth. As you know, we are a long way from being able to do these things. But until we *have* done this we cannot say that the potentialities of the method are exhausted.

In summary, it seems to me that an improved basic understanding of many aspects of exploration seismology is needed; we know that the potentialities of the method are far from being exhausted. Basic research should lead us to new avenues of geophysics—avenues that in turn will lead to an improved ability to find the oil reserves that we will need.

There may be some doubt in the minds of some of our geophysicists as to the good that will come of the government's project Vela Uniform, about which you will hear more tomorrow, but there is no doubt in my mind that the program will contribute much to our basic knowledge of geophysical principles. It is virtually impossible for American scientists to spend in excess of thirty million dollars without this being true, and *I am certain* that it will be true if the program is turned over to experienced professional exploration geophysicists, as it should be. Then phenomena, like decoupling, which has been known to the geophysical industry for thirty years, would be kept in proper perspective. Since these projects involve all the fields of geophysics, and in seismology all the frequencies involved in seismic sound transmission, the benefits to our industry will be widespread. In a few years we can reasonably expect this new knowledge to change and improve geophysical exploration.

While we are on the subject of research, it has been a thought of mine for some time that we could progress much faster in developing these new tools, ideas, instruments, and techniques if we could arrange an interchange, at some level, in the developments in basic research. I believe there is a level which could be found, if the idea was pursued by our research people, where information could be exchanged without prejudicing the position of the organization originating the information. It would be a tremendous help if only the studies which developed negative results were exchanged. This would save many valuable

man hours of fruitless research. One of the members of our research committee recently remarked to me that they had nothing to do but arrange a program for the annual meeting. Here, gentlemen, is something you can get your teeth into.

Now comes the most important aspect of this address. I have said earlier during my tenure of office that the reduced level of geophysical activity had its rewards; that it was possible for the oil companies, mining companies, and geophysical contractors to weed out the deadwood, to release the inefficient and unqualified employees. I still think this is true, but, unfortunately, the adverse publicity and the lack of foresightedness on the part of some managements is causing an alarming number of competent geophysicists—field and research men—to leave the geophysical industry. One large oil company man told me recently that he has had several of his best research scientists leave the field in recent months against the wishes of the company. Another, a vice-president of a large international oil company, told me within the last few days that they had been unable to recruit qualified scientists to engage in geophysical research. This is very serious. Now is the time when we need top-flight men to carry on the development work which is so vitally needed. We certainly need all the experienced men we now have, around whom to build for the expanded activity which must come within a few years. We also need new talent—bright young men with new ideas—and unless there is an overall change in management policy we not only will not be able to recruit this new talent, but we will continue to lose qualified experienced personnel from our industry.

There are only 566 students in all categories studying geophysics in the United States today, and fewer and fewer graduates are going on for advanced study. Furthermore, to make matters worse, a large number of the geophysics majors graduating with advanced degrees are not entering the field of exploration geophysics.

What can be done about this? It seems to me that we must reverse the trend by showing that there is and will be a future for geophysics and geophysicists. These people must be encouraged by management, not only by promotions, but by appreciable salary increases.

At least one major oil company is not losing any of its qualified geophysicists. This company's management has demonstrated to its geophysicists that it has high regard for geophysical training by placing many of these men in high and key management jobs. This type of encouragement from other organizations will tend to attract the high quality personnel that we so vitally need in our industry, and will keep the ones we now have for our future expansion.

There was one note of pessimism in the address of Sir Stephen Gibson mentioned previously. This is the ability of the exploration industry to find the oil and gas reserves that we will need in the future at competitive prices. This is certainly a challenge to us and I, for one, believe that the exploration industry with its inventiveness and ingeniousness will find these reserves, but it is up to us to provide the incentive for our personnel to stay up-to-date, and competitive.

GEOPHYSICS, VOL. XXVI, NO. 2 (APRIL, 1961), PP. 138-157, 22 FIGS.

INTERPRETATION OF SYNTHETIC SEISMOGRAMS*

R. L. SENGBUSH,† P. L. LAWRENCE,† F. J. McDONAL†

Abstract: A linear filter model of the complicated seismic process can be formulated by assuming that (1) the layering of the earth is described by the continuous velocity log, (2) the shot pulse is time-invariant and propagates as a plane wave with normal incidence, and (3) all multiples, ghosts, and other noise are negligible. Then, the model earth with discrete layers can be considered a filter whose impulse response is the set of reflection coefficients. The set of reflection coefficients becomes the reflectivity function when the model earth has a continuously varying velocity. By definition, the reflectivity function is the derivative of the logarithm of velocity, where both are functions of two-way travel time. The input to this filter is the time-invariant shot pulse. The output is a synthetic seismogram that contains the reflectivity function filtered by the shot pulse; in other words, it consists of primary reflections only. Since the filter is linear, the input and the filter may be interchanged, the reflectivity function becoming the input and the shot pulse becoming the filter.

A non-mathematical discussion of the reflections from simple, ideal velocity layering shows that: (1) The reflection from a step velocity function is the shot pulse itself. (2) Thin beds produce a differentiated shot pulse. (3) Beds which approximate a square pulse in velocity produce a pair of shot pulses, with the second delayed in time and reversed in phase with respect to the first. The composite reflection has its greatest amplitude when the layer thickness (in two-way travel time) is one-half the basic period of the shot pulse. This situation is called "tuning." The strongest reflections on field records result when the shot pulse is tuned to the velocity layering. (4) Ramp-transition zones (linear increase in the logarithm of velocity) produce integrated shot pulses at the changes in slope of the velocity function.

A correspondence can be established between the velocity function and the synthetic seismogram by shifting the velocity function later in time. The shift is required because of "filter delay." The amount of filter delay is related to the impulse response waveform, which, in the case of the synthetic seismogram, is given by the reflection from a step velocity function.

INTRODUCTION

This paper presents a treatment of the fundamentals of synthetic seismograms from the view of linear filter theory. It gives a detailed description of a linear filter model of the seismic process in the earth, and discusses reflections from simple velocity layering. The paper also contains a discussion of depth-time correspondence between the earth and the related seismogram, and some examples comparing field records and synthetic seismograms.

The paper is written for the benefit of seismic interpreters. We want it to be of practical value to them, as we believe a thorough understanding of synthetic seismograms will contribute to a better interpretation of field records. For this reason, we have chosen a descriptive rather than a mathematical treatment of the subject, and have emphasized the qualitative, and in some instances quantitative usefulness of the model in assisting in the interpretation of field records. For those who are interested in the mathematical treatment, an appendix containing the pertinent steps and formulae is given at the end of the paper.

THE LINEAR FILTER MODEL OF THE SEISMIC REFLECTION PROCESS

This paper presents a linear filter model[1] of the actual seismic process in the real earth. The linear filter model is a mathematical model, and has the two characteristics common to all mathematical models:

1. The models are precisely defined mathematically.

[1] The model is a linear, passive, time-invariant filter, which for simplicity we will call a linear filter.

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† Socony Mobil Oil Co., Inc., Dallas, Texas.

2. The models are only approximations to reality; that is, while the mathematical relations are precise, they do not correspond to reality under all conditions.

The primary purpose of a model is to answer some questions, but not all questions about the "thing" that is being modelled. The usefulness of a particular model lies in its success in giving correct answers. The answers may be quantitatively inaccurate, but qualitatively useful. Even when the answers are partially wrong, the model is useful as it provides a framework for the description of deviations from ideality—and we may be led to a better model. Models are important from another standpoint—and this is very important in the case of the linear filter model of the actual seismic process—in that they force a certain precision of thought on the part of the problem formulator that had not been demanded by the relatively nebulous sort of thinking that preceded the model.

The linear filter model that is discussed in this paper was first presented in a very significant paper by Peterson, Fillipone, and Coker (1955). The Peterson model is defined by the following properties:

1. The model earth is transversely isotropic, and is characterized in the z-direction by a continuous velocity function $v(z)$ that is obtained from a continuous velocity log. The density function $\rho(z)$ of the model is related to $v(z)$ by $\rho(z)=k[v(z)]^m$, where k and m are constants. In the special case where $m=0$, $\rho(z)=k$.
2. The shot pulse propagates in the z-direction as a plane wave, thus striking the layers at normal incidence.
3. Reflections result exclusively from velocity changes due to the assumed relationship between density and velocity.
4. Only primary reflections are allowed—all types of "noise" such as ground roll, ghosts, and multiples are excluded.
5. The shot pulse waveform is time-invariant; that is, its shape and amplitude are constant and do not change with travel time.

Peterson called the output of his model the synthetic seismogram. The fact that the synthetic[2] is similar to the field record to a marked degree in many instances means that the model frequently gives the correct answers, which is an indication that the model approaches reality. This is sufficient reason to study the model in detail.

[2] The noun, synthetic, is used for brevity in place of synthetic seismogram.

We will digress briefly and review the well-known properties of a linear, passive, time-invariant filter. Taking the adjectives in order:

1. Linear means that the output is linearily related to the input; that is, if the input $f_1(t)$ produces an output $o_1(t)$, and if another input $f_2(t)$ produces the output $o_2(t)$, then the input $f_1(t)+f_2(t)$ will produce the output $o_1(t)+o_2(t)$. Also, if the input is $Af_1(t)$, where A is a constant, the output will be $Ao_1(t)$.
2. Passive means that the filter has no internal sources; that is, it responds only when it has an input.
3. Time-invariant means that the properties of the filter are independent of time; that is, if $f_1(t)$ produces $o_1(t)$, then $f_1(t\pm\tau)$ gives $o_1(t\pm\tau)$.

A standard method of characterizing a filter is by its impulse response (Figure 1). An impulse[3] as an input will produce a characteristic transient waveform as an output—this waveform is called the impulse response, $g(t)$. There are two restrictions on $g(t)$ in any physically realizable filter (meaning one that can be constructed with physical elements):

1. $g(t)=0$ for $t<0$.
2. $g(t)\to 0$ for $t\to\infty$.

In other words, a physically realizable filter cannot respond before the impulse is applied, and the effect of the impulse must eventually die out.

Thus, a linear filter is a black box with an input and an output. The impulse response $g(t)$ is a characteristic of the filter, and as such, belongs in the box. Any given input $f(t)$ will be modified in passing through the box, and the output will be a function of both $f(t)$ and $g(t)$. Mathematically the output will be given by convolving $f(t)$ with $g(t)$. The mathematical operation of convolution is

[3] An impulse $\delta(t)$ has the following properties:

$$1.\ \delta(t)=\begin{cases}\infty, & t=0\\ 0, & t\neq 0.\end{cases}$$

$$2.\ \int_{-\infty}^{+\infty}\delta(t)dt=1.$$

Thus, an impulse is infinite at the only point where it is not zero, and it approaches infinity in such a way that its area remains finite. Impulses are useful mathematical concepts, but they are not physically realizable. However, it is possible to approximate an impulse with functions that are realizable, such as a tall, thin square pulse.

designated by a star, and is defined by the integral relationship of equation (1),

$$(1)\quad o(t) = f(t) * g(t) = \int_0^t f(\tau)g(t-\tau)d\tau,$$

where $o(t)$ is the output waveform. Convolution is a commutative operation, hence

$$(2)\qquad f(t) * g(t) = g(t) * f(t).$$

This property of convolution shows that for a given input it is immaterial which of the two waveforms $f(t)$ or $g(t)$ is considered the input and which is considered the impulse response of the filter. The two possibilities with actual filters are shown in Figure 2.

Now we will show why the reflection process in the Peterson model is a filter process. Consider first the model with one interface in Figure 3. The interface is parallel to the surface and is located at a depth d_1. The velocity above the interface is v_1 and the velocity below is v_2. In this model the shot pulse propagates as a plane wave with normal incidence on interfaces, hence in the special case where the density is constant, the reflection coefficient at the interface is given by the familiar relation

$$(3)\qquad R_1 = \frac{v_2 - v_1}{v_2 + v_1}.$$

As the reflection coefficient is not frequency discriminatory, the reflection has the same waveform except for amplitude as the incident shot pulse. Considering the shot pulse to have unit amplitude, the reflection amplitude is given by equation (3). The polarity of the reflection is the same as the shot pulse if v_2 is greater than v_1; it is reversed in polarity if v_2 is less than v_1. The onset of the reflection occurs at the time τ_1, which is the two-way travel time to the interface. Symbolically, the shot pulse is designated $f(t)$ and the reflection $R_1 f(t-\tau_1)$.

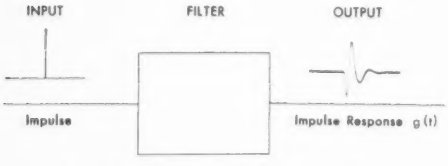


FIG. 1 Impulse response of a linear filter.

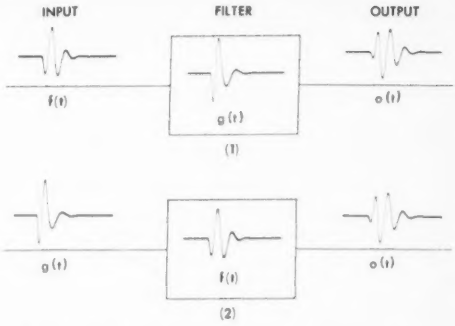


FIG. 2. The impulse response and input are interchangeable in a linear filter.

This model can be extended directly to "n" velocity interfaces as shown in Figure 4, which for sake of clarity shows non-vertical incidence. Each reflection has the same waveform as the time-invariant shot pulse, but each has its own characteristic amplitude, polarity, and time delay. The output from this model is the summation of all the reflections. Calling the output waveform $o(t)$,

$$o(t) = R_1 f(t-\tau_1) + R_2 f(t-\tau_2) + \cdots. \quad (4)$$

This can be written concisely as a summation

$$o(t) = \sum_{i=1}^{n} R_i(\tau_i) f(t-\tau_i), \quad (5)$$

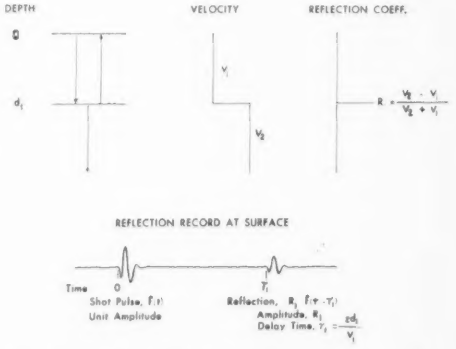


FIG. 3. A model with one interface produces a reflection record which consists of the shot pulse and one reflection. Due to the assumption that the shot pulse is time-invariant, the reflection has the same waveform as the shot pulse.

where the notation $R_i(\tau_i)$ indicates that the reflection coefficients are a function of two-way travel time.

The summation of equation (5) describes the reflection process in the "n" layered model. Mathematically this equation is a convolution, hence the reflection process in the model is a linear filter process. The earth can be considered a black-box filter whose impulse response is the set of reflection coefficients spaced properly in time. The shot pulse is the input. As with any filter the output is dependent upon both the input and the impulse response. The model can be extended from "n" discrete layers to a continuous velocity distribution in the limit as the layer thickness approaches zero. Then the summation of equation (5) becomes an integral of the form (1).

The complicated velocity layering of the earth is obtained from a continuous velocity log. The CVL can be sampled to give an "n" layer model, and the reflection amplitude at each interface can be calculated using equation (3). At this point Peterson introduced a significant approximation, the logarithmic approximation, to the reflection coefficient. In equation (3) v_2 can be replaced by $v_1+\Delta v$ giving

$$R_1 = \frac{(v_1 + \Delta v) - v_1}{(v_1 + \Delta v) + v_1}, \qquad (6)$$

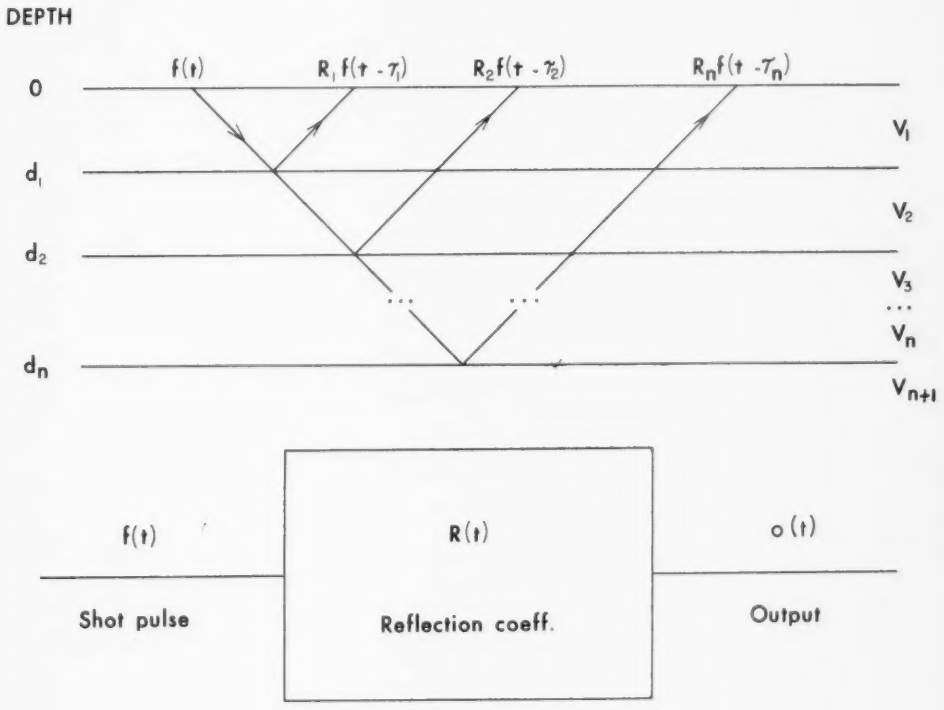


FIG. 4. A model with "n" interfaces produces a reflection record which consists of the shot pulse and "n" reflections. Due to the assumption of linearity, the output is obtained by adding the reflections algebraically.

$$R_1 = \frac{\Delta v}{2v_1 + \Delta v} \cdot \tag{7}$$

If Δv is small compared to v_1, which will be true if the CVL is sampled at close enough intervals, equation (7) can be written as an approximation

$$R_1 \approx \frac{1}{2}\,\frac{\Delta v}{v_1}, \tag{8}$$

$$R_1 \approx \frac{1}{2}\,\Delta \log v_1. \tag{9}$$

The approximation is very good for reflection coefficients less than 0.3.

If density variations are considered in the model, v must be replaced in equation (9) by the acoustic impedance ρv, where ρ is the density. However, if the density is related to the velocity by the general expression, $\rho = kv^m$, where k and m are constants, the acoustic impedance becomes

$$\rho v = kv^{m+1}. \tag{10}$$

In equation (9) the reflection coefficient becomes

$$R \approx \frac{1}{2}\,\Delta \log kv^{m+1}, \tag{11}$$

$$R \approx \frac{1}{2}\,[\Delta \log k + (m+1)\Delta \log v],$$

$$R \approx \frac{m+1}{2}\,\Delta \log v. \tag{12}$$

In this case also, the reflection coefficient is proportional to the change in the logarithm of velocity.

The continuous velocity log gives the velocity distribution as a function of depth. This is converted to velocity as a function of two-way travel time. In the discrete layer case the reflection amplitude is determined by the reflection coefficients, as given by equation (3) or by the approximation of equation (9). In the continuous case the set of reflection coefficients is replaced by the reflectivity function, designated $r(t)$. The reflectivity function can be developed from equation (7) by letting the sampling interval approach zero as a limit. Equation (7), which is an exact expression, becomes

$$\lim_{\Delta t \to 0} \frac{R}{\Delta t} = \lim_{\Delta t \to 0} \frac{\Delta v}{\Delta t}\,\frac{1}{2v + \left(\frac{\Delta v}{\Delta t}\right)\Delta t}, \tag{13}$$

$$= \frac{1}{2v}\left(\frac{dv}{dt}\right), \tag{14}$$

$$= \frac{1}{2}\,\frac{d \log v}{dt}, \tag{15}$$

The coefficient of $\frac{1}{2}$ is merely a gain factor and can be ignored. The logarithm of velocity as a function of time will be called the velocity function. Then the derivative of the velocity function with respect to time is defined as the reflectivity function,

$$r(t) \triangleq \frac{d \log v(t)}{dt} \cdot \tag{16}$$

If the velocity function is continuous, the reflectivity function will also be continuous, and *equation (16) will be an exact expression* in comparison to equation (9) which is an approximation. The steps required to convert a velocity log to the reflectivity function are shown by the block diagram in Figure 5.

The reflection process is a filter process; therefore, there are two alternate ways of considering the filtering process in the model (Figure 6). The normal way of viewing the reflection process is to consider the shot pulse as the input and the reflectivity function as the impulse response of the filter. However, the input and the filter can be interchanged, making the input the reflectivity function and the shot pulse the impulse response of the filter. This is the analog method of preparing synthetic seismograms, as described by Peterson. The filtering that acts upon $r(t)$ has been divided into two parts, the shot pulse $f(t)$ and the filtering external to the earth $e(t)$. The latter includes the combined effect of all instruments plus geophone coupling. These two filters are in cascade, hence the synthetic seismogram $s(t)$ is given by

$$s(t) = r(t) * f(t) * e(t). \tag{17}$$

We will use the definition, $b(t) \Delta f(t) * e(t)$ to simplify the notation. Then

$$s(t) = r(t) * b(t). \tag{18}$$

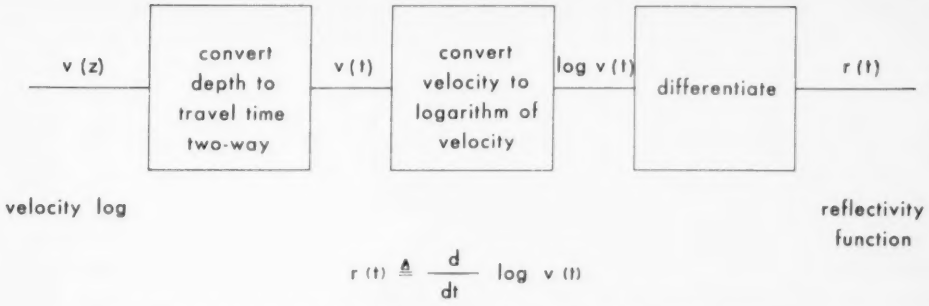


FIG. 5. The reflectivity function is obtained from the continuous velocity log in three steps.

The concept of the shot pulse as a filter should not be confused with the concept of earth filtering (Figure 7). Earth filtering results in a broadening of the shot pulse waveform with travel time, because of the increasing loss in amplitude of the higher frequencies by attenuation and scattering. The broadening of the waveform with travel time occurs simultaneously with the reflection process. This introduces time-variance into the reflection process in the real earth.

In this model all earth filtering is lumped together and applied at the source. Then the shot pulse waveform is considered to be time-invariant. Since most of the pulse broadening occurs close to the shot, this is a reasonable assumption over a large portion of the record, provided we are considering times beyond approximately $\frac{1}{2}$ second.

OTHER MATHEMATICAL MODELS

The invention of the continuous velocity log made it possible for the first time to characterize the earth in all its complexity by a parameter that is directly related to reflections on seismic records.

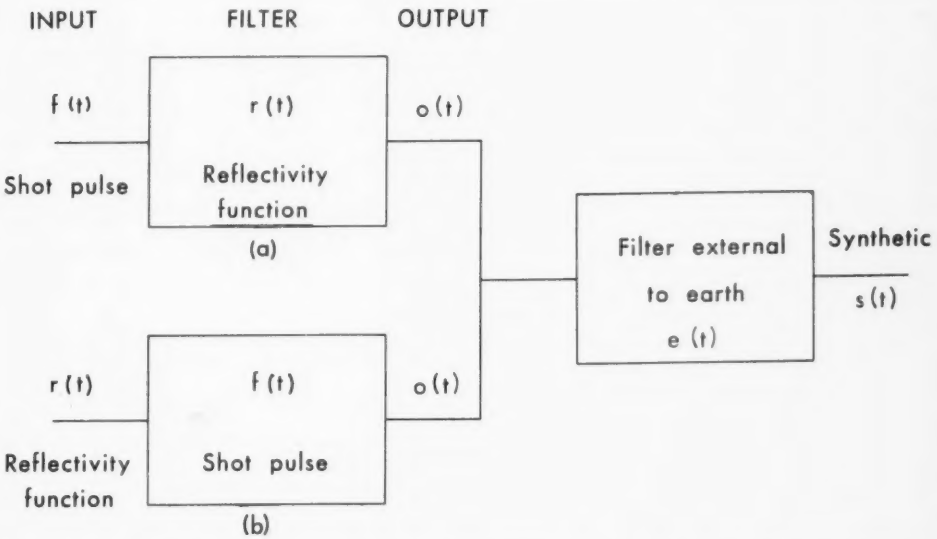


FIG. 6. The reflection process in the model is a linear filter process, and as a result there are two alternative ways of representing the process. Either the shot pulse or the reflectivity function can be either the input or the impulse response.

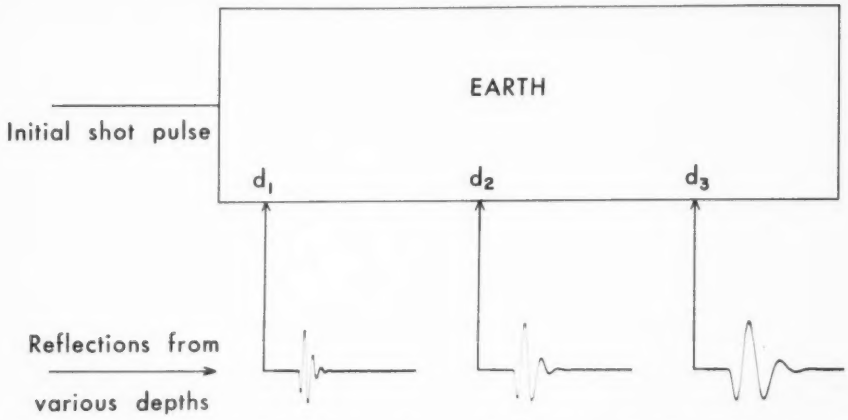


FIG. 7. The shot pulse in the actual earth is time-variant, resulting in a broadening of the reflections with time. The assumption of time-invariance in the model requires that the distributive effects of earth filtering be lumped at the source and applied to the initial shot pulse.

Before the CVL, the mathematical model that was used was what we call the "thick-layer" model. It had the same properties as the Peterson model except that in the absence of definite velocity information, the thick layers were characterized by uniform velocities within each layer. This model contained a countable number of interfaces, which gave rise to a countable number of reflections—of course, there could be some overlapping of reflections to give a composite reflection—with "noise" in between reflections. Linear filter theory as described by equation (5) precisely defines the thick-layer model.

The refinement introduced by Peterson of using the continuously varying velocity obtained from a CVL brought the model closer to reality. It is an "ideal" model in that the synthetic seismogram output contains nothing other than primary reflections. Other models have been introduced which depart from the ideal and become more realistic by introducing ghosts, reverberations, and other multiples.

Berryman (1958) and Wuenschel (1960) have described models which contain all multiples. These two models have the same properties as the Peterson model, except for the fourth property. The continuous velocity function from the CVL is sampled to give an "n" layered earth, and all reflections, primary and multiple, are obtained by solving the one-dimensional wave equation, taking into account the reflection and transmission effects at each boundary. In place of the reflectivity function $r(t)$ as defined by equation (16), they obtain a more complicated function which contains both primary and multiple reflectivity, which is then convolved with the seismic pulse. The seismic pulse as described by Wuenschel includes the combined effects of the shot pulse, instrument response, and ghosts.

Backus (1959) introduced water reverberations into the model by means of a filter in cascade with $b(t)$. This additional filter, call it $h(t)$, includes both the reverberations (multiple reflections) within the water layer and the location of the detector. The water-reverberated seismogram is given by

$$s_h(t) = r(t) * b(t) * h(t). \qquad (19)$$

Lindsey (1960) introduced ghosts into the model in the same way that Backus introduced reverberations. In the case of ghosts, the additional filter can include both the velocity layering above the shot and the additional attenuation in the ghost path. Equation (19), which will apply to both the Backus and Lindsey models with proper choice of $h(t)$, is written with $r(t)$, but the Berryman-Wuenschel multiple reflectivity function could be used in place of $r(t)$. Of course, the main objective of both Backus and Lindsey was not to determine $s_h(t)$ from a known $r(t)$, but rather to eliminate $h(t)$ from the field records.

A more realistic model would use a time-

variant sh ulse. The mathematics is only slightly more complicated, and time-variant synthetics could be easily calculated using digital computers. With analog equipment, an adequate approximation to time-variance can be accomplished piece-wise by using different filters for different sections of the record if the time-variance is slow with respect to the time constants of $b(t)$.

We do not intend to discuss further any of the models other than the Peterson model. We will continue with a discussion of the reflections from some simple velocity functions as a basis for the more general velocity functions obtained from CVL's.

SIMPLE VELOCITY FUNCTIONS

Now consider the reflections from the simple velocity layering in Figure 8. The simplest layering is a single interface between two beds of different but uniform velocity. This layering has a step velocity function. We know that it produces a reflection having the same waveform as the shot pulse. Its amplitude and polarity are determined by the velocity contrast across the interface.

A thin, high velocity layer in a uniform velocity section has a spike (a tall, thin square pulse) for a velocity function. The reflection from such a layer approximates the differentiated shot pulse.

A linear increase in velocity with depth corresponds to a linear increase in the logarithm of velocity with time. This type of velocity function is called a ramp. A ramp is an integrated step, hence the reflection from a ramp is the integrated shot pulse. The onset of the reflection is at the change in slope. The amplitude of the reflection is proportional to the change in slope. If the change in slope is doubled, the amplitude is doubled. If the change in slope is negative, the reflection is reversed in polarity.

Consider now a three-layer case where the first and third layers have the same velocity and the velocity of the middle layer is larger (Figure 9). The velocity function is a square pulse. There are two reflections; a positive one, beginning at t_1, and a negative one, beginning at t_2. The composite reflection is the sum of the two. The square pulse will be discussed by considering the ratio of $\Delta t/T$, where Δt is the bed thickness expressed in two-way travel time and T is the basic period of the shot pulse as defined in Figure 11. The ratio is important, not the layer thickness nor the basic period individually.

When the bed thickness Δt is large compared to the length of the shot pulse, the square-pulse layering is merely two isolated steps. The resulting reflections are distinct, and each has the same waveform as the shot pulse. The polarity of the second reflection is opposite to that of the first.

When Δt equals one-half the basic period of the shot pulse the amplitude of the composite reflection becomes a maximum, approaching twice the amplitude of the reflection from a step. This increase in amplitude is called tuning; that is, the shot pulse is "tuned" to the velocity layering.

As the $\Delta t/T$ ratio decreases from one-half, the

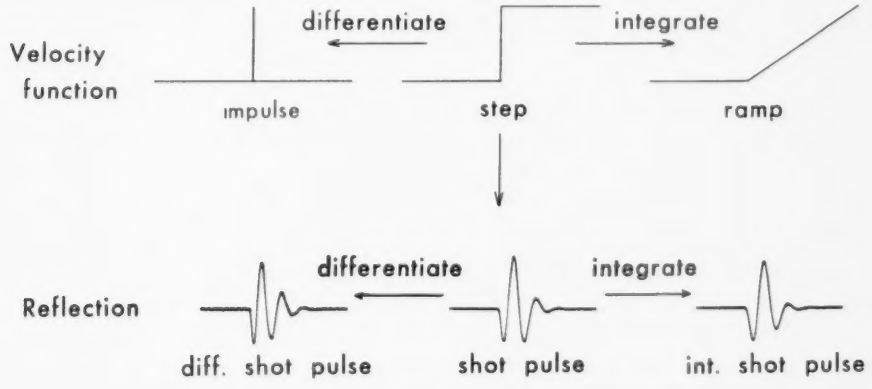


FIG. 8. Reflections from step, impulse, and ramp velocity functions.

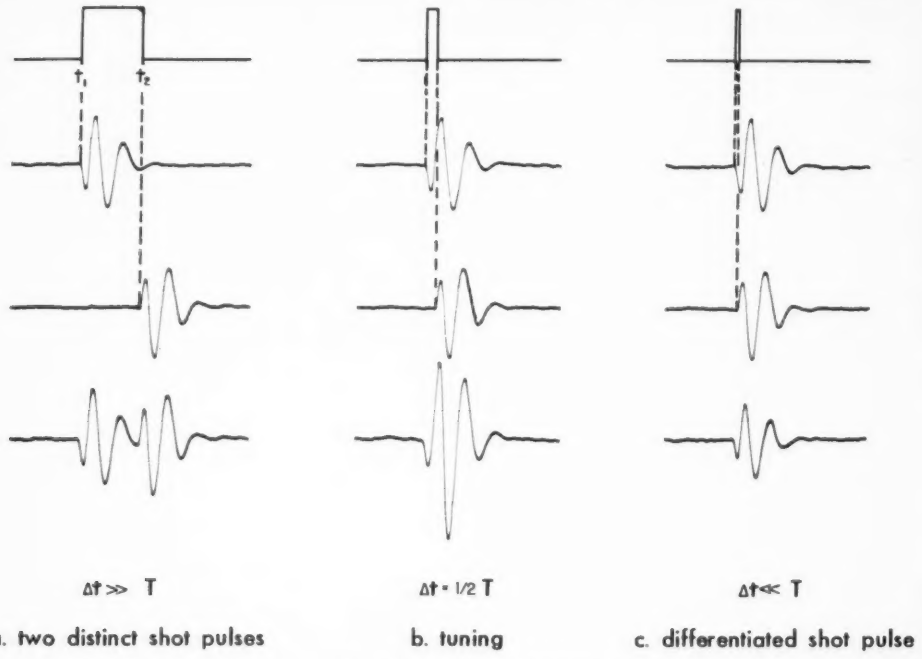


FIG. 9. Reflections from square-pulse velocity functions, showing the three critical $\Delta t/T$ ratios.

amplitude of the composite reflection decreases. The square pulse is approaching a spike; therefore, the reflection approximates the differentiated shot pulse. For ratios less than 0.2 the reflection amplitude is decreased by one-half whenever the ratio is decreased by one-half. This is exactly the effect of differentiation.

The reflections from a series of square-pulse velocity zones of different thicknesses are shown in Figure 10. This figure shows the effect of varying the $\Delta t/T$ ratio. The reflection from the step velocity change at the right end of the figure shows the shot pulse used on each trace. These pulses have the same amplitude and the same fundamental shape, but different basic periods. In effect, the fundamental waveform is stretched or compressed in time to give the various basic periods. Horizontally, each trace forms a set of

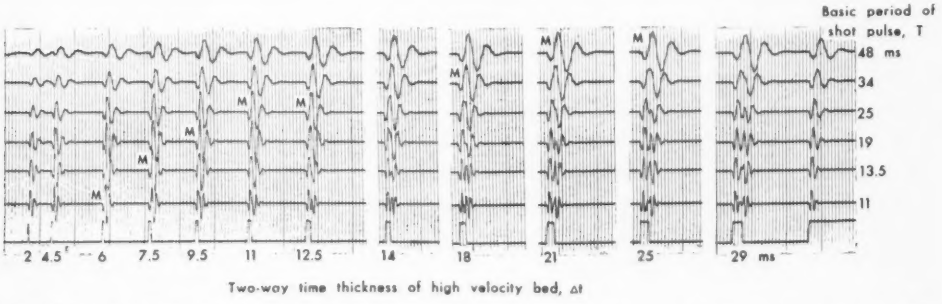


FIG. 10. Model study of square-pulse velocity functions showing effect of changing either the bed thickness or the basic period of the shot pulse. The maximum reflection amplitude (M) occurs when $\Delta t/T \approx \frac{1}{2}$.

reflections where the basic period of the shot pulse is held constant and the bed thickness is varied. Vertically, there is another set of reflections where the bed thickness is held constant and the basic period is varied. The tuning effect can be seen by following either a horizontal or a vertical set of reflections. As the ratio approaches one-half, the reflection amplitude becomes a maximum. The largest reflections for each horizontal and vertical set are labeled M on the figure.

The amplitude of the composite reflection is plotted in Figure 11 as a function of the $\Delta t/T$ ratio. The amplitude is normalized by considering the reflection from the step to be unity. As an example in the use of the figure, let $T = 30$ ms and the velocity in the layer be 10 ft/ms. The reflection from a layer 75 ft thick has twice the amplitude of the reflection from an infinitely thick layer, while one 22 ft thick produces the same reflection amplitude, and one 11 ft thick has half that amplitude. It is of interest to note that the 22-ft layer is only one-fourteenth of the apparent wave length of the shot pulse, and its reflection is as large as when the layer is infinitely thick.

Consider now a three-layer case where the middle layer of thickness Δt has a linear increase in the logarithm of velocity and the layers on

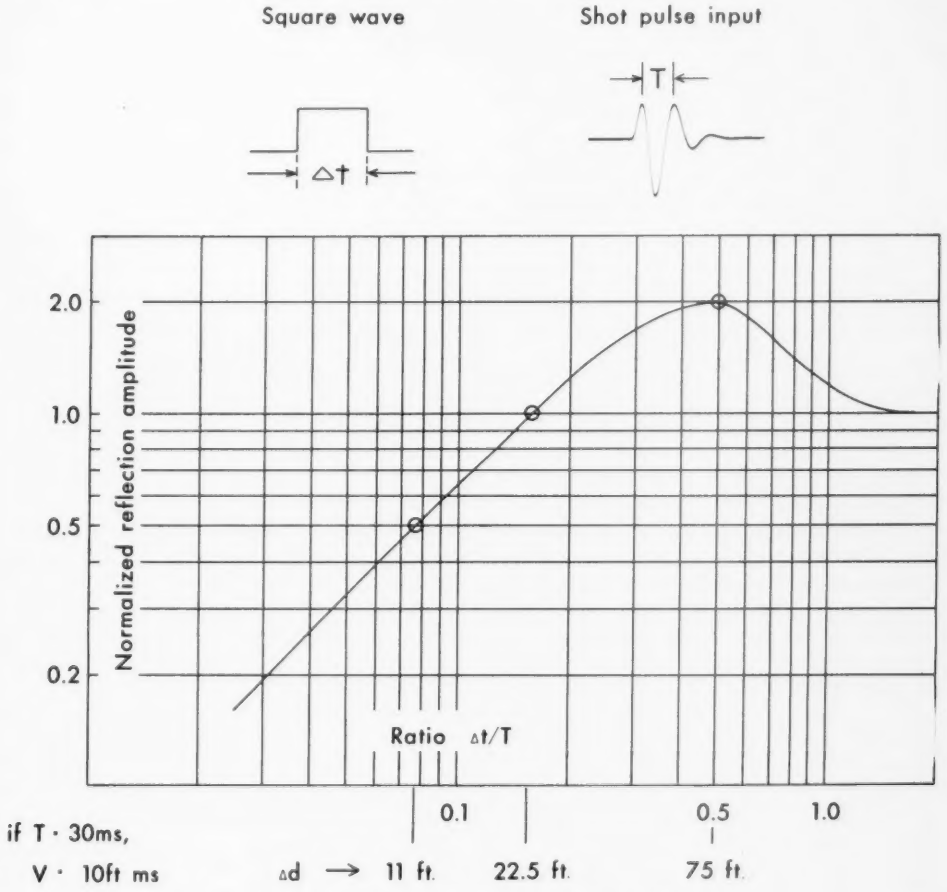


FIG. 11. Plot of normalized reflection amplitudes as a function of the $\Delta t/T$ ratio, for square-pulse velocity functions.

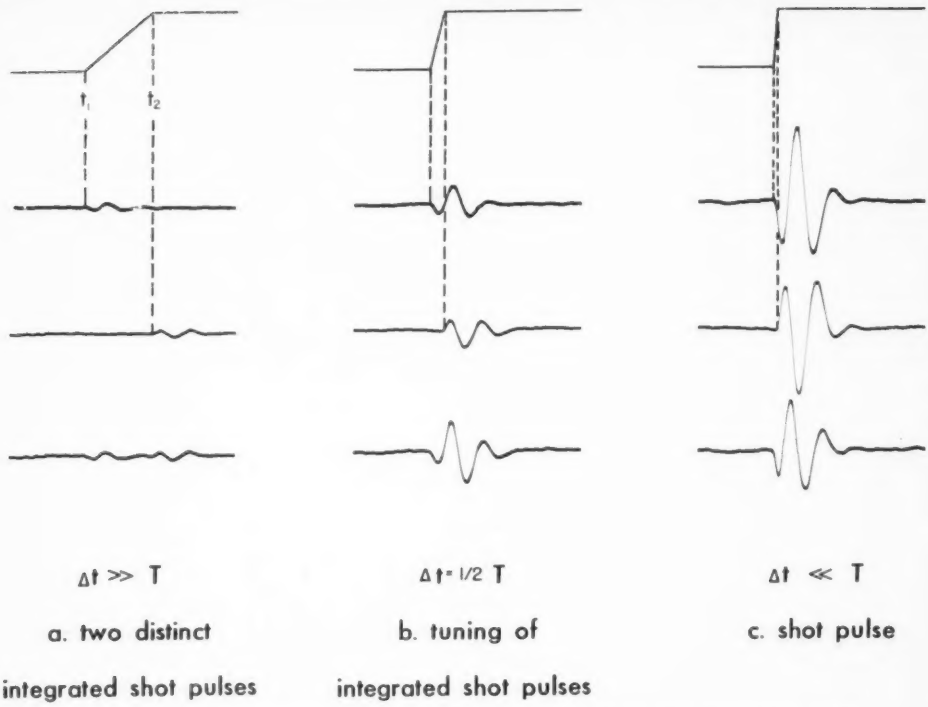


FIG. 12. Reflection from ramp-transition velocity functions, showing the three critical $\Delta t/T$ ratios.

either side have constant velocity (Figure 12). This is called a ramp-transition velocity function. The changes in slope at t_1 and t_2 are of equal magnitude but opposite sign. Hence this layering reflects two integrated shot pulses of equal magnitude, a positive one beginning at t_1 and a negative one beginning at t_2. The amplitude of each reflection is proportional to the change in slope, hence is inversely proportional to Δt in this case.

The ramp-transition zone will be discussed by considering the effect of the $\Delta t/T$ ratio on the amplitude of the composite reflection. When Δt is large compared to T, the two reflections are distinct. Their amplitudes decrease as the $\Delta t/T$ ratio increases. Doubling the ratio decreases their amplitudes by one-half. This is exactly the effect of integration.

When Δt is small compared to T the ramp-transition function approaches a step function, consequently the reflection waveform is the same as that of the shot pulse.

When the $\Delta t/T$ ratio is approximately one-half there is a tuning effect due to the constructive addition of the two reflections. However, each reflection is reduced by the factor $1/\Delta t$, with the net result that the maximum amplitude of the tuned reflection is always less than the amplitude from the step.

The reflections from ramp-transition layering are shown in Figure 13. As in the figure for the square-pulse layering, there is a horizontal and a vertical set of reflections. The amplitudes of the composite reflections are plotted as a function of the $\Delta t/T$ ratio in Figure 14. The bulge in the curve near $\Delta t/T = \frac{1}{2}$ is due to tuning.

A triangular velocity function that is tuned to the shot pulse is shown in Figure 15. The changes in slope at t_1 and t_3 are of equal magnitude and both are positive while the change in slope at t_2 is twice that magnitude and is negative. Thus, the composite reflection is the sum of three integrated shot pulses. The first and third are positive with equal magnitude. The second is negative with twice that magnitude.

Tuning of two or more reflections results in increased reflection amplitude due to constructive addition. Additional properly spaced interfaces will continue to increase the maximum amplitude until the number of equally spaced interfaces is the same as the number of half-cycles in the shot pulse. Further increase in the number of interfaces will cause no further increase in the maximum amplitude.

Figure 16 shows the reflections from simple velocity functions. Included are the reflections from one, two, four, and eight interfaces. The shot pulse has three major half-cycles. On the third and fourth traces the shot pulse is approximately tuned to the square-pulse layering. The maximum amplitude of the tuned reflection increases progressively as the number of interfaces is increased from one (the step) to two and from two to four. Further increase in the number of interfaces to eight does not increase the maximum amplitude of the reflection.

Other velocity functions will give maximum amplitude reflections when they are tuned to the shot pulse. This is demonstrated in Figure 17 where square pulses are compared with sine and impulse-type velocity functions having the same fundamental period. In part *b* high-frequency signals are superimposed upon the fundamental velocity functions of part *a* to give the type of log $v(t)$ input that is found frequently in practice. The shot pulse is tuned to the fundamental velocity layering. Therefore, it filters out the superimposed high-frequencies and produces reflections which are similar to the reflections from the fundamental velocity functions.

CORRESPONDENCE BETWEEN DEPTH AND TIME

The previous development shows that the reflection from a single interface has a unique onset time on the reflection record. The single interface is a point in depth in the earth and has an equivalent point in time on the velocity function. However, each point in depth d_i produces a response $b(t)$, beginning at the equivalent time point t_i and extending later in time for duration equal to the total length of $b(t)$ (designated A in Figure 18). Conversely, the entire depth zone of thickness A' above d_i (A' is equivalent to A in time) contributes to the reflection amplitude at a time point t_i. Thus, the filtering action of $b(t)$ shifts the synthetic (and field) record later in time with respect to the velocity function. The shift is called "filter delay."

The filter delay is related to the impulse response waveform. In the case of the synthetics, the impulse response $b(t)$, which is the shot pulse

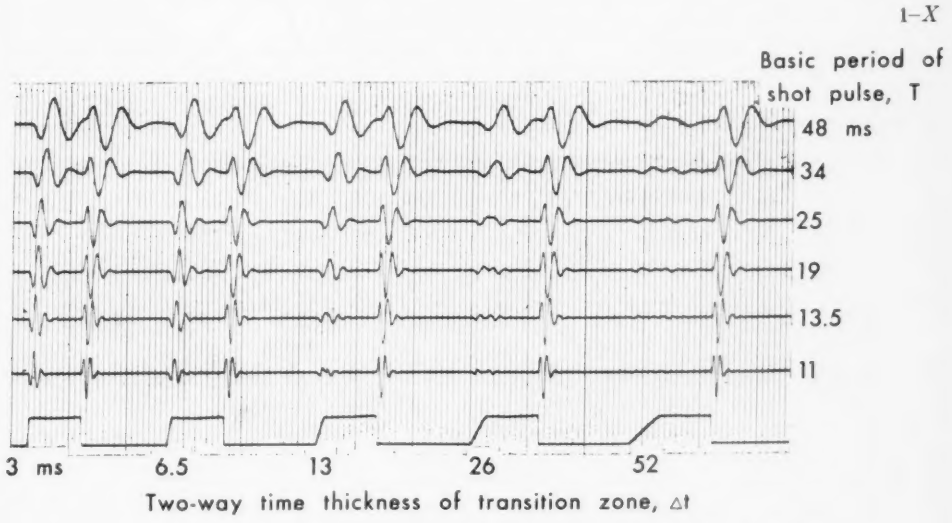


FIG. 13. Model study of ramp-transition velocity functions showing effect of changing either the bed thickness or basic period of shot pulse.

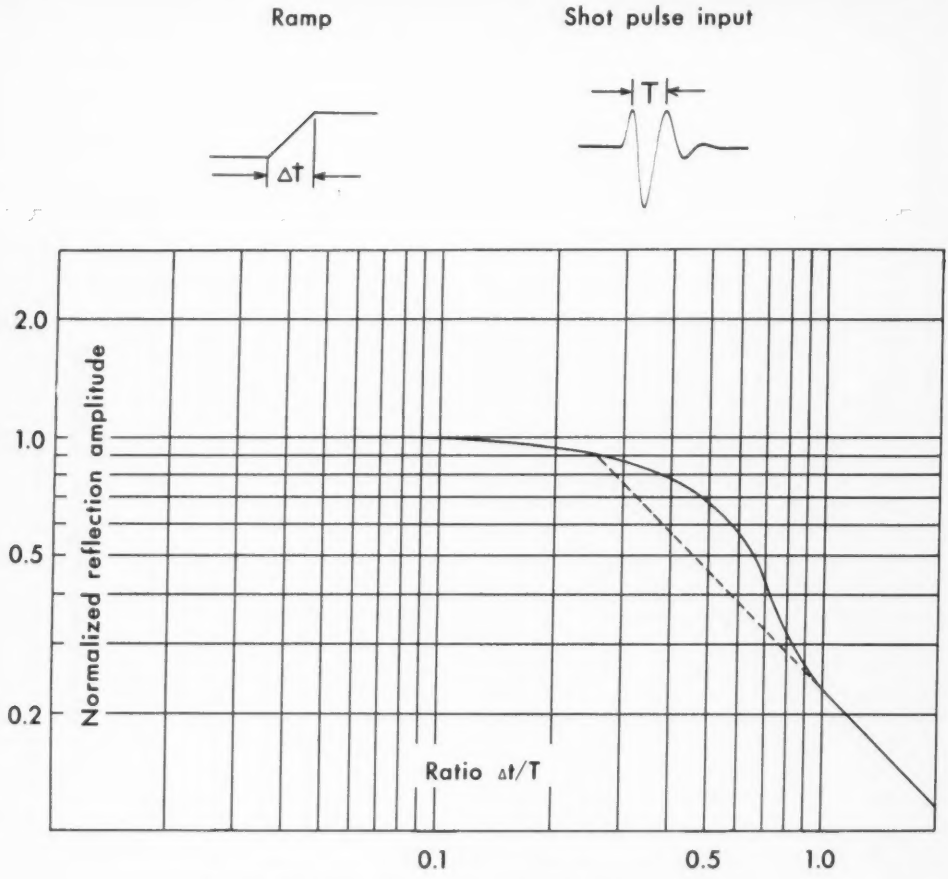


FIG. 14. Plot of normalized reflection amplitudes as a function of the $\Delta t/T$ ratio, for ramp-transition velocity functions.

as modified by the external filtering, is given by the reflection from a step velocity function. The filter delay is constant when $b(t)$ is time-invariant, while it becomes progressively larger depending upon the time-variance in the case of field records.

Consider the two synthetic records made from an idealized velocity log in Figure 19. The shot pulses have different character, as shown by the reflection from the step velocity changes. The step is a point in depth. It produces a reflection which extends 70 ms on the upper trace and 55 ms on the middle trace. The two shot pulses have the same basic period. The upper one has two major peaks and one major trough; the middle one has two major troughs and one major peak. The upper one has some extra legs, but they are small and contribute little to the resulting synthetic. Thus, the two pulses have similar shapes except for a phase reversal and a relative time displacement. The best correlation between the two shot pulses is the major trough on the upper trace with the major peak on the middle trace, with a relative time displacement between them of 12 ms. Notice that the phase reversal is not due to an inconsistency in the initial breaks of the shot pulses, as the reflection from a step velocity change from low to high velocity (the first step on the direct trace) has an initial downbreak

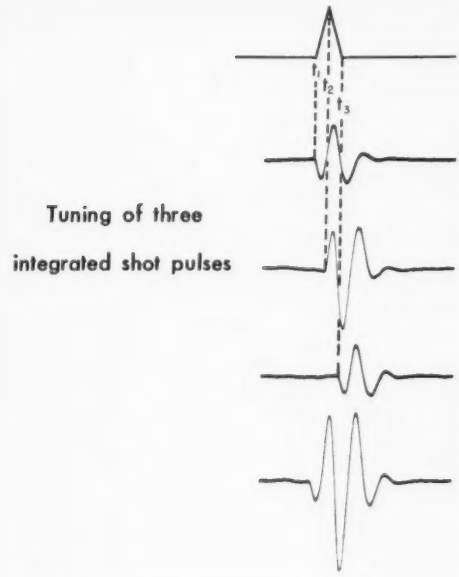


FIG. 15. Reflections from a triangular velocity function, under the condition of optimum tuning.

on both traces. The polarity reversal and time delay of the pulse on the upper trace are due to additional filtering of the upper shot pulse.

After comparing the shot pulses on the two traces, it is not surprising that the resulting synthetics have similar character, but are out of phase and displaced in time by 12 ms for the best correlation between them. These observations follow directly from the similarities and differences between the shot pulses. In Figure 19 a time shift has been made between the upper and middle traces to make the correlation more obvious.

Consider now the correspondence between the velocity function and the synthetic on the middle trace. A filter delay of 15 ms on the synthetic establishes a correlation between peaks on the synthetic and high velocity zones on the velocity function. The two traces have been time-shifted by this amount in Figure 19 to make the comparison more obvious. Another good correlation could have been made by shifting the velocity function 30 ms in which case a high velocity zone would correspond to a trough on the synthetic. Thus, the synthetic does not have a unique cor-

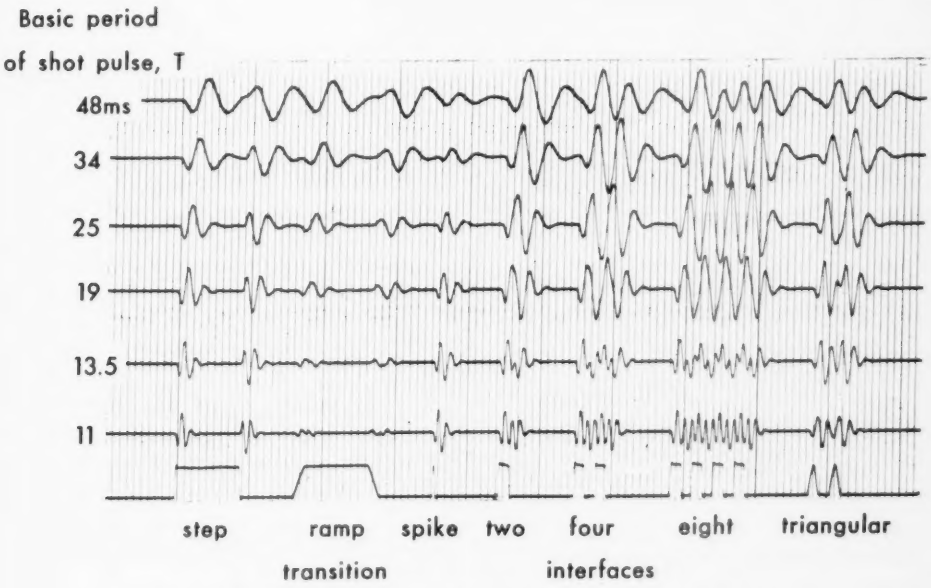
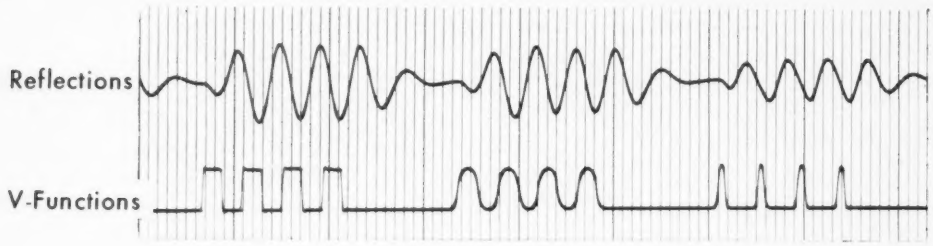
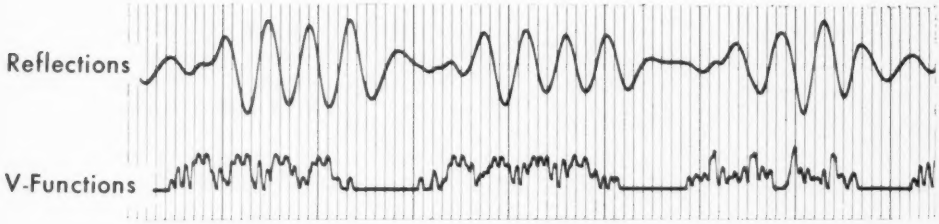


FIG. 16. Synthetic seismograms made from a variety of simple velocity functions, using different shot pulses.



a. Shot pulse tuned to simple periodic functions



b. Same shot pulse and same periodic functions with random high frequency function superimposed

FIG. 17. Tuned reflections, showing how the shot pulse filters out the high frequencies superimposed on the tuned-velocity functions.

relation with the velocity function although there is usually a "best" correlation.

The correlation that was made between high velocity zones and reflection peaks, with a time delay of 15 ms, is applicable for tuned and spike velocity layering. Notice that the spike in Figure 19 correlates with the first peak of the reflection.

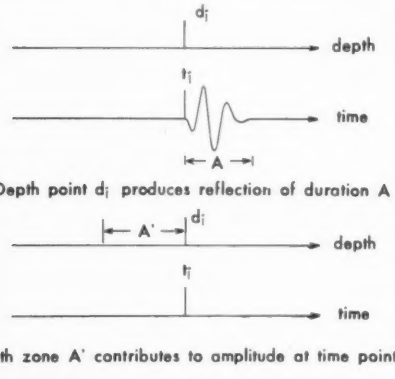


FIG. 18. Correspondence between depth and time.

However, the step interface correlates with the zero crossing preceding the first peak, and the onset of the ramp-transition zone correlates with the trough preceding the above zero crossing. This follows directly from the fact that the reflections from spike, step, and ramp velocity functions are differentiated, flat, and integrated shot pulses, respectively, and a constant time delay from the onset of the reflections will pass through a peak, zero crossing, and trough, respectively.

COMPARING SYNTHETICS WITH FIELD RECORDS

In making synthetic seismograms by analog methods the velocity function is used as the input to a filter, and the filter is adjusted to give a satisfactory comparison with the field record.

The filtering used in making a synthetic record can be considered correct if the synthetic matches the field record. There are three criteria for a good match:

1. The field and synthetic records should match in character. They should have the same in-

terval time between large reflection events. They should have the same "dead" zones.

2. When the field and synthetic records have the best character match, they should also have the same filter delay. In other words, there should be no relative time-shift between them on best match.
3. The polarities of the synthetic and field records should be consistent. If the polarity of the field record is established by making the first breaks kick down, a step velocity change in the earth from low to high velocity will produce a reflection that initially breaks down on the field record. The polarity of the synthetic can be set to the polarity of the field record by placing an isolated step on the velocity function and observing the initial break of its reflection.

There are many possible reasons for a poor match between the synthetic and field records. They fall into three classes:

1. The filtering on the synthetic may not duplicate the filtering on the field record. Remember that the field record contains a shot pulse filter as well as all filtering external to the earth, such as geophone coupling, geophone response, amplifier filter, AGC, and so forth.
2. The assumptions made in formulating the model may not hold sufficiently well in the actual earth. The poorest assumption is that the field record contains primary reflections only. Noises that may be present on the field record (multiples, ghosts, surface waves, etc.) do not appear on the synthetic. The assumption that density is constant, or proportional to velocity, is poor in some formations, especially those containing salt and anhydrite.
3. The original velocity log is subject to errors. The most serious is due to washouts in shale or salt sections. With one-receiver logs the recorded velocity is too low in washouts. This results in exaggerated amplitude of the reflections and in timing errors of up to 15 ms on the synthetic record. With two-receiver logs the timing errors are minor but washouts may produce false character.

The filtering used in making synthetics is generally determined empirically, using two bandpass filters—one matching the filter used on the field record and the other simulating the filtering action of the shot pulse. These are the most restrictive parts of the over-all filtering of the field record. The recording filter is known; therefore, the second one is varied to give the best match between field and synthetic records. The precise waveform of the shot pulse is unknown, but it is a bandpass filter. In fact it *is the factor* that determines the "seismic band."

Three examples comparing field and synthetic records are shown in Figures 20–22. For each field record, one high-quality trace was obtained by mixing several traces after static time-correcting for weathering and elevation variations. Column charges were used in the first two cases to reduce the strong ghosts that were present.

The synthetic records in each case have the same polarity as the field record, as determined from the initial downbreak of the reflection from the artificial step placed near the beginning of

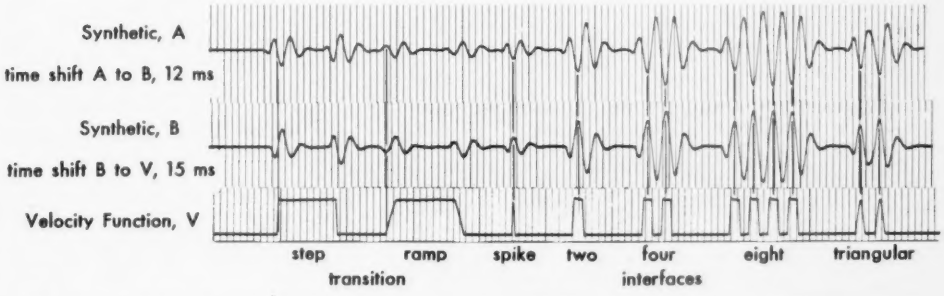


FIG. 19. Correlation of synthetic seismograms with a velocity function. A correspondence is established between the largest reflections (the tuned reflections) and the velocity function by shifting the velocity function later in time.

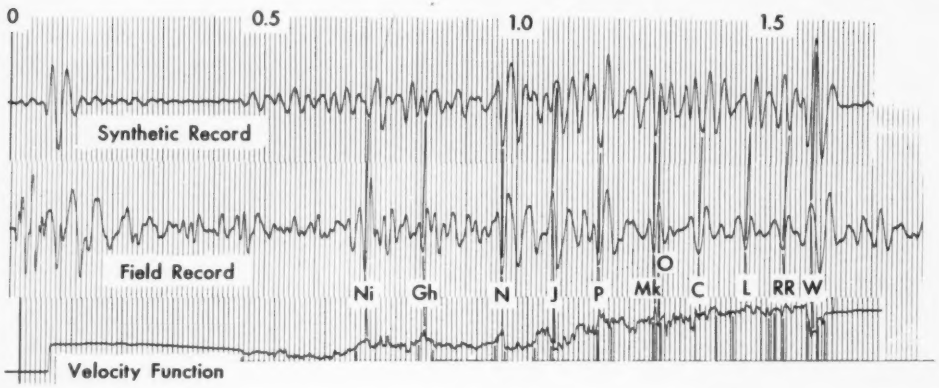


FIG. 20. Comparison of field and synthetic records from a well in the Willston Basin.

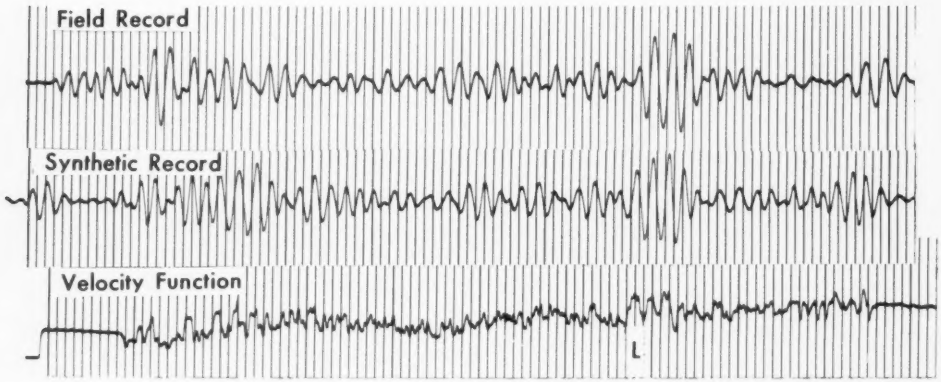


FIG. 21. Comparison of field and synthetic records from a well in South Texas.

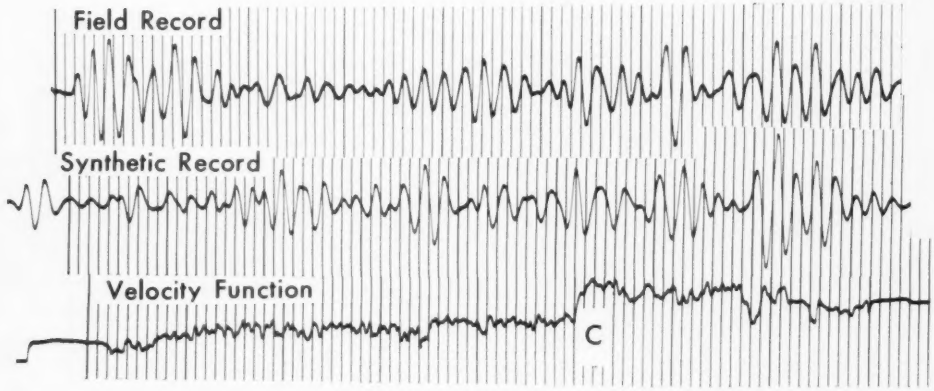


FIG. 22. Comparison of field and synthetic records from a well in North Central Texas.

each velocity function. This fulfills the third criterion for good matching.

The synthetic and field records in Figures 20 and 21 are displayed with zero relative time shift, in accordance with the second criterion. A time shift has been allowed in Figure 22 because the continuous velocity log in this well was not checked by a geophone survey. Thus, the time scale of its velocity function is not anchored to the "exact" times of a survey.

The first criterion, the character match, is the most important. The character matches shown in the three examples are the best that were achieved using two bandpass filters, one to simulate the shot pulse and one to simulate the recording system. In each case the velocity function has been time-shifted to the right to establish a correspondence between it and the synthetic record.

The well in Figure 20 is in the Williston Basin. A correspondence was established between the synthetic and the velocity function by equating the N trough and the high velocity peak in the Newcastle. The velocity function was shifted 23 ms to the right to line up these two points. The troughs marked Ni, Gh, P, Mk, C, L, and RR correspond to high velocity zones in the Niobrara, Greenhorn, Piper, Minnekahta, Charles, Lodgepole, and Red River, respectively. The peaks marked J, O, and W correspond to low velocity zones in the Jurassic (Morrison), Opeche, and Winnipeg, respectively.

The synthetic and field records were recorded with a 15–134 cps filter, and in addition, the synthetic was filtered using a 30–43 cps "shot pulse" filter. This shot pulse filter gave the best match of the Newcastle reflection.

The synthetic and field records are timed below datum and are displayed with zero relative time-shift between them. The N trough has an arrival time of 972 ms on both, showing that the criterion of no relative time-shift is satisfied. The minor variations of a few milliseconds between corresponding events on the two traces are probably due to minor errors inherent in the time scale of the velocity function. Presumably the time scale of the field record is above reproach.

The reflection from the isolated step introduced at the left of the velocity function not only establishes the polarity but also shows the waveform of the shot pulse. The basic period T of the shot pulse is 29 ms. By using this value of T in Figures 11 and 14, the relative effectiveness of square-pulse and ramp-transition zones in producing reflections can be determined. For example, the Newcastle can be resolved into the sum of a ramp transition zone whose thickness Δt is 22 ms, and a negative step that is delayed 22 ms behind the onset of the transition zone. The $\Delta t/T$ ratio of the ramp transition zone equals 0.76, giving a normalized reflection amplitude of 0.35 using Figure 14. But by direct measurement from the velocity function one finds that the ramp amplitude is only 0.71 as large as the negative step; therefore, if the amplitude of the negative step reflection is considered unity, the amplitude of the ramp transition reflection will be $0.71 \times 0.35 = 0.25$. Thus, the negative step at the base of the Newcastle is four times more effective than the ramp transition zone in producing a reflection.

The well in Figure 21 is in South Texas. The strongest and most consistent reflection in this area is the tuned reflection produced by the cyclic variation in velocity in the alternating sands and shales beginning with the Lopez (L) sand. The velocity function of these sands and shales has a basic period of about 20 ms, which is equivalent to a basic frequency of about 50 cps. This frequency falls within the passband of the shot pulse filter, which was empirically determined to be 40–79 cps. The shot pulse filters out the high frequencies that are superimposed on the 50 cps basic signal in the same manner as shown in Figure 17(b). In Figure 21 the velocity function has been time-shifted about 25 ms to the right to establish the correspondence between high velocity zones and peaks on the field record.

The well in Figure 22 is in North Central Texas. It illustrates the point that reflections from a step velocity change in the earth are ordinarily smaller than reflections from tuned layers. The Canyon (C) limestone has a step-like velocity change from about 11 to 17 ft/ms, but its reflection is considerably smaller than the later-arriving tuned reflections that are produced by alternating limestones and shales.

APPENDIX

A. *The Complex Domain*

The relationship between the field and synthetic records can be written concisely using the Laplace transforms of the time functions. The Laplace transform of $f(t)$ is defined by

$$F(s) = \int_0^\infty f(t)e^{-st}dt.$$

A function in the time domain $f(t)$ is transformed into a function of a complex variable $F(s)$. Mathematical operations are simplified in the complex domain. The following operations are equivalent:

Time Domain	*Complex Domain*
1. Integration;	division by s
$\int f(s)dt$	$\frac{F(s)}{s}$.
2. Differentiation;	multiplication by s
$\frac{df(t)}{dt}$	$sF(s)$.
3. Time shift by a units;	multiplication by e^{-as}
$f(t-a)$	$e^{-as}F(s)$.
4. Convolution;	multiplication of transforms
$\int_0^t f_1(\tau)f_2(t-\tau)d\tau$	$F_1(s)F_2(s)$.

The convolution integral of equation (1) becomes $O(s)=F(s)G(s)$ in the complex domain. Multiplication of transforms is commutative, hence $F(s)G(s)=G(s)F(s)$. It is not necessary that one of the corresponding time functions is considered the input to a filter and the other the impulse response.

The reflectivity function is the derivative of the velocity function,

$$r(t) = \frac{dw(t)}{d(t)},$$

where $w(t)=\log v(t)$. Thus, $R(s)=sW(s)$. The filtering process shown in Figure 6 becomes $S(s)=F(s)R(s)E(s)$, where $S(s)$ is the transform of the synthetic seismogram and $E(s)$ is the transform of the impulse response of the external filter. Also, $S(s)=sF(s)W(s)E(s)$.

The simple velocity functions in Figures 8, 9, 12, and 15 have simple transforms, hence give rise to simple reflections as tabulated below.

Velocity Function, $w(t)$	*Transform of Velocity Function, $W(s)$*	*Transform of Reflection, $O(s)=sW(s)F(s)$*	*Reflection, $o(t)$*
1. Unit impulse			differentiated shot pulse,
$\delta(t)$	1	$sF(s)$	$f'(t)$
2. Unit step,			shot pulse,
$u(t)$	$\frac{1}{s}$	$F(s)$	$f(t)$
3. Ramp,			integrated shot pulse,
$\frac{A}{\Delta t}tu(t)$	$\frac{A}{\Delta t}\frac{1}{s^2}$	$\frac{A}{\Delta t}\frac{F(s)}{s}$	$\frac{A}{\Delta t}f^{-1}(t)$
4. Unit square pulse			pair of shot pulses,
$u(t)-u(t-\Delta t)$	$\frac{1}{s}[1-e^{-\Delta ts}]$	$F(s)[1-e^{-\Delta ts}]$	$f(t)-f(t-\Delta t)$
5. Ramp transition,			pair of integrated shot pulses,
$\frac{A}{\Delta t}[tu(t)-(t-\Delta t)u(t-\Delta t)]$	$\frac{A}{\Delta t}\frac{1}{s^2}[1-e^{-\Delta ts}]$	$\frac{A}{\Delta t}\frac{F(s)}{s}[1-e^{-\Delta ts}]$	$\frac{A}{\Delta t}[f^{-1}(t)-f^{-1}(t-\Delta t)]$
6. Triangle,			three integrated shot uplses,
$\frac{A}{\Delta t}[tu(t)-2(t-\Delta t)u(t-\Delta t)+(t-2\Delta t)u(t-2\Delta t)]$	$\frac{A}{\Delta t}\frac{1}{s^2}[1-2e^{-\Delta ts}+e^{-2\Delta ts}]$	$\frac{A}{\Delta t}\frac{F(s)}{s}[1-2e^{-\Delta ts}+e^{-2\Delta ts}]$	$\frac{A}{\Delta t}[f^{-1}(t)-2f^{-1}(t-\Delta t)+f^{-1}(t-2\Delta t)]$

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GEOPHYSICS, VOL. XXVI, NO. 2 (APRIL, 1961), PP. 158–168, 6 FIGS.

UNDERGROUND AND SURFACE GRAVITY SURVEY, LEADWOOD, MISSOURI*

S. T. ALGERMISSEN†

Abstract: A surface gravity survey consisting of 214 stations covering approximately four square miles was conducted over and adjacent to the North Leadwood Mines at Leadwood, Missouri. A corresponding survey of 278 stations was carried out in the mine workings. A method of reducing underground gravity observations is outlined. The principal factors limiting the accuracy of the underground observations are given. Methods for determining rock densities are described. A comparison of the surface and underground gravity maps shows that major Precambrian knobs were revealed by both surveys. Smaller structures not shown on the surface map were revealed by the underground survey. Anomalous density areas between the level of the two surveys were easily located.

INTRODUCTION

The area investigated comprises approximately four square miles near and including the town of Leadwood, Missouri, about sixty miles southwest of St. Louis. The survey consisted of 214 surface gravity stations over the North Leadwood Mine and 278 stations underground in the mine workings. The North Leadwood mine is one of the large lead mines of the Southeast Missouri lead district, known locally as the "Lead Belt." The principal ore mineral is galena, but some zinc is found as sphalerite.

The objectives of the survey were to obtain a comparison of gravity observations taken on two different levels, and in addition, show up the known structures and perhaps some unknown structures associated with the ore deposits in the mine. No attempt was made to locate concentrations of lead directly by means of the gravity survey. The galena is finely disseminated through the rock and the average grade of ore is approximately three to four percent.

GENERAL GEOLOGY

The geology of the Southeast Missouri lead deposits has been described in detail by a number of authors. The most complete descriptions are those of Buckley (1908), Tarr (1936), James (1949–52), and Ohle and Brown (1954). Buckley's description and other early reports of the district are limited by the fact that several of the major ore bodies were only slightly developed at the time they were written.

Description of the Leadwood area

The rock succession is a Precambrian basement of igneous rocks unconformably overlain by a sedimentary series which is Upper Cambrian in age. The lithology of the Precambrian igneous rocks is not well known in the Leadwood area. Surface and underground diamond drill holes have located these rocks in only three localities. In all three localities, the rock type was logged as "porphyry" a term used locally to indicate a rhyolite porphyry. It is possible that at least a portion of the Precambrian basement beneath the North Leadwood Mine is composed of granite since the Precambrian hills at the nearby Hayden Creek Mine are known to be granite (Ohle, 1952). The Precambrian surface was a mature topography of considerable relief which was subjected to a long period of erosion. It was covered in Upper Cambrian time with a blanket of basal sand, known as the Lamotte sandstone, which contains some shale and dolomitic sand and in some localities, residual igneous boulders near the base. Overlying the Lamotte sandstone is the Bonneterre formation, which is the prin-

* Presented at the 27th Annual Meeting of the Society at Dallas on November 14, 1957.

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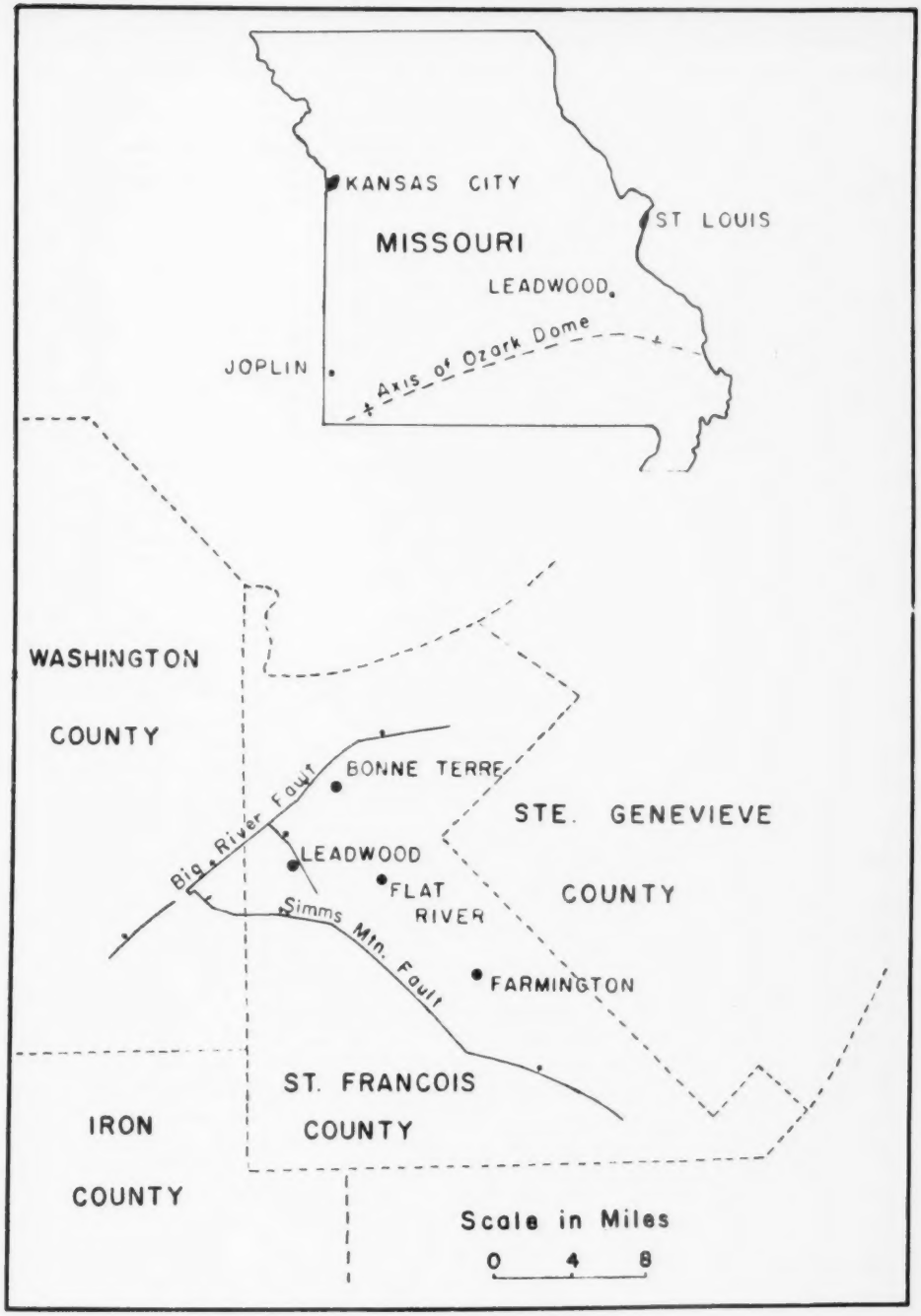

FIG. 1. Location map showing major faults of the Leadwood Area.

cipal ore bearing formation in the Lead Belt. The North Leadwood Mine is at or near the base of the Bonneterre. The Bonneterre is about 375–400 ft thick and outcrops in the Leadwood area. It is composed principally of dolomite with some limestone and minor amounts of shale. The formation has been subdivided by geologists of the St. Joseph Lead Company into units numbering from top to bottom: 1, 3, 5, 7, 10, 12, 15, and 19. A detailed description of the units is given by Ohle and Brown (1954). Omitted numbers in the zoning of the formation indicate certain rock types with restricted distribution and limestone types found outside the mining district which are the equivalent of the dolomite beds within the district. Upper Cambrian dolomites and limestones are found above the Bonneterre. They are not known to contain appreciable ore in the Leadwood area.

Important structural features at Leadwood

Ohle and Brown (1954) and other writers as well, have recognized three principal types of structure influencing Lead Belt ore bodies: (1) domal or anticlinal structures related to buried Precambrian knobs and ridges, (2) sedimentary arch structures of depositional origin and (3) fracture zones.

Three dome structures in the Bonneterre formation which reflect buried Precambrian knobs are present in the North Leadwood Mine. They are known as the Leadwood, Schultz, and Switchback knobs. Some of the largest tonnages of ore in the mine have been taken from the basal part of the Bonneterre formation over and around the periphery of these knobs. The Switchback knob projects into the Bonneterre formation. The Schultz and Leadwood Knobs are covered by a thin layer of Lamotte sandstone. The presence of the Schultz and Leadwood Knobs is reflected in the contour map of the top of the Lamotte sandstone (Figure 2).

Sedimentary arch structures of depositional origin have also been important in localizing ore bodies. These arch structures, primarily present near the base of the Bonneterre formation (19-zone) were presumably formed by current action in a northeast direction during the deposition of the Bonneterre. The controlling factor in the deposition of the arches is not clear.

Faults and fracture systems appear to be related to ore trends in some cases, but the larger ore trends seem to be related to depositional features. Snyder and Odell (1958) have emphasized the importance of sedimentary breccias in the localization of ore.

DENSITY MEASUREMENTS

The results of density measurements on 100 diamond drill cores and a generalized stratigraphic column are shown in Figure 3. Some of these cores are from the North Leadwood Mine and others are from the surrounding mining district. The numbered zones represent subdivisions of the Bonneterre formation recognized in the mining district.

The density computed from a density profile (Nettleton, 1939) over a hill near Leadwood is also shown in Figure 3. It is evident that the major density contrast of about 0.3 gm./cc. is present between the Lamotte sandstone and the remainder of the rock types present. It is probable that only structures associated with the mature Precambrian topography and/or thickening or thinning of the Lamotte sandstone would be revealed by a gravity survey.

Another method of obtaining a suitable density value for the rocks between the surface and the mine was used. The gravity value at a point on the surface was compared with the gravity reading obtained directly beneath it in the mine using the relationship (Hammer, 1950):

$$\Delta g = (F - 4\pi\gamma\sigma)\Delta H + \Delta T. \qquad (1)$$

Where Δg is the vertical change in gravity between a point on the surface and a point underground, F is the free air vertical gradient (.0904 milligals per foot), γ is the gravitational constant, σ is the density, ΔH is the vertical distance between the point on the surface and the point underground, and ΔT is the change in terrain correction over the interval ΔH. If no anomalous variations in the vertical gradient occur, a value for σ may be computed since all the other quantities in equation (1) may be determined. During the course of the survey, eight pairs of surface and underground gravity observations were used to compute average rock density values for the rocks between the surface and the mine workings. Table I indicates the computed average densities and the formation outcroppings where the surface station was located. All of the underground stations were in the Bonneterre formation.

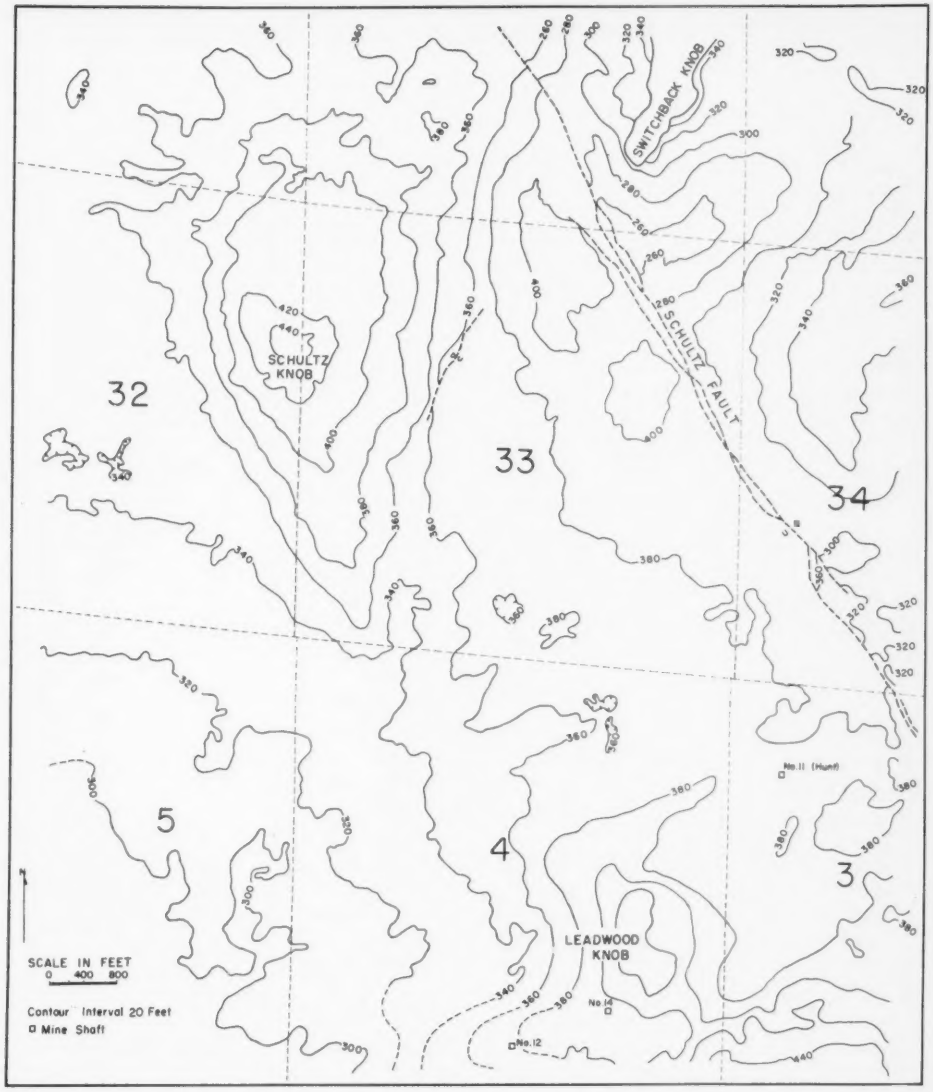

FIG. 2. Structure contour map of the top of the Lamotte sandstone.

It was possible to locate the surface station directly over the corresponding underground station because of the close network of surface elevations, and the accurate surface and mine maps maintained by the St. Joseph Lead Company. The principal sources of error in determining the densities in Table I are the error in corrections for mined-out areas, terrain effects and station elevation error. Consideration of these errors result in a determination of density by this method to an accuracy of about ± 0.03 grams/cm.^{3}.

THE SURFACE GRAVITY SURVEY

The 214 surface gravity stations were reduced in the standard manner using density of 2.60.

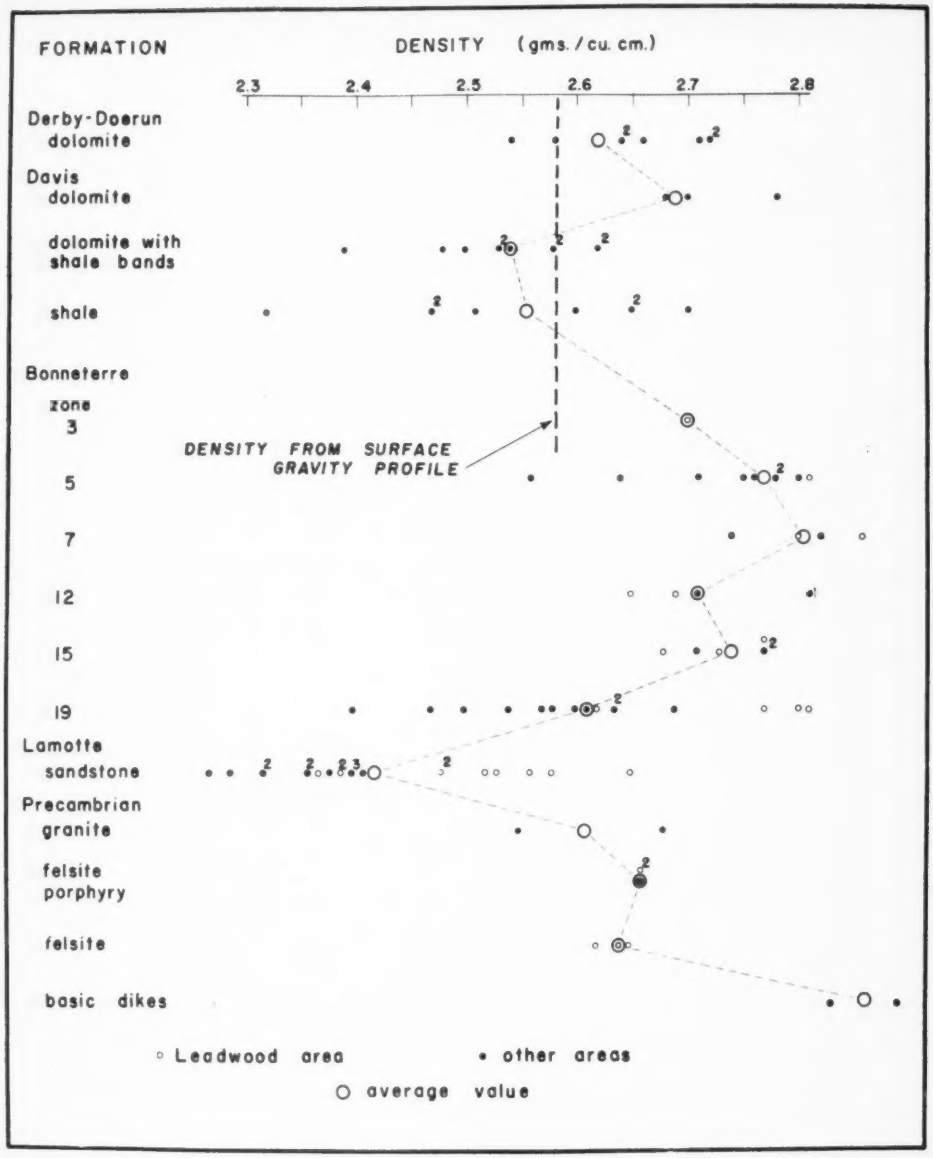

FIG. 3. Density distribution from rock samples and surface density profile.

The densities obtained from diamond drill cores of the rocks within the range of topographic relief yielded an average density of about 2.65. However, the range of density values was large and the density of some of the more porous samples could not be accurately determined. A density profile indicated a near surface density average of 2.58. As previously discussed, the comparison of eight pairs of surface and underground gravity readings yielded an average density of 2.61. The comparison of surface and underground readings sampled a thicker rock section than that

TABLE I. DENSITIES DETERMINED BY COMPARISON OF SURFACE AND SUBSURFACE GRAVITY

Formation Outcropping	Density (gms./cm³)
Derby-Doerun	2.61
Bonneterre	2.60
Bonneterre	2.62
Davis	2.68
Davis	2.58
Davis	2.61
Davis	2.59
Bonneterre	2.62

present within the range of surface topography. A density of 2.60 represents reasonably well the average rock density within the range of surface topography. Terrain corrections were computed for topography within a radius of 8,578 ft of the station using Hammer's (1939) terrain chart. All of the surface gravity observations are believed accurate to 0.1 milligal.

Figure 5 is a Bouguer gravity map of the area over the North Leadwood Mine. The map indicates a gradient of about 2.2 milligals per mile in a northeast direction. The regional gravity map of Missouri prepared by the Missouri Geological Survey, based on gravity stations at approximately ten-mile intervals, shows a gradient of about 0.7 milligal per mile northeast. The regional gravity will not be discussed in detail in this paper, but it is believed to be controlled principally by the Simms Mountain and Big River fault systems near Leadwood (Figure 1). The increased gradient at Leadwood is believed to be caused by the local buried Precambrian topography and variations in thickness of the Lamotte sandstone.

The Leadwood and Schultz knobs show clearly as gravity maxima on this map. This would be expected since the thickness of the Lamotte sandstone is probably not greater than 20 ft over the top of these structures. Actually, the gravity anomalies over these knobs are considerably distorted by the effect of mined-out areas. Both the Leadwood and Schultz knobs are associated with large ore bodies and consequently the lower Bonneterre formation is extensively mined-out over and on the periphery of these structures. The average stope height is 20 to 30 ft, but some stopes over the Schultz knob are 100 ft high. Using vertical cylinders (Nettleton, 1942) as an approximation to the mined-out areas, the maximum effect of stopes on the gravity values is estimated at 0.3–0.4 milligals over the Schultz knob and 0.4–0.5 milligals over the Leadwood knob. For surface stations over other parts of the mine where large stopes are not present, the effect of drifts and small stopes was estimated at 0.1 milligal or less.

Because of the small areal extent of the surface and underground surveys and the uncertainty regarding the regional gravity, no residual gravity map was prepared.

THE UNDERGROUND GRAVITY SURVEY

The 278 underground gravity stations were located at points in the mine previously surveyed by the St. Joseph Lead Company. The elevations are known to 0.2 ft. It was not always possible to maintain an even station distribution throughout the mine since many of the older stopes and drifts are inaccessible because of water. Where adequate gravity coverage was not sacrified, readings were taken in drifts rather than stopes because of the nature of the corrections for mined-out areas.

Figure 4 illustrates the type of corrections necessary for the reduction of the underground stations. For the interval between the elevation of the station and sea level, the normal combined free air-Bouguer correction is computed for the height h_1 and added to the gravity reading. The attraction of the mass above the underground station must also be added to the gravity reading at the station. If we assume for the moment that the surface of the ground is absolutely flat, the correction for the mass above the station is simply the Bouguer correction for a slab of thickness h_2 (Figure 4). Actually, the ground surface is not flat and a correction for topography must be applied to the underground station. For the topography above the Bouguer slab of thickness h_2, a positive terrain correction is applied since the Bouguer correction does not compensate for this mass. For topography below the Bouguer slab, a negative terrain correction is necessary. In practice the elevation of the point on the surface vertically above an underground station was determined to ± 1 ft and in extreme cases to ± 2 ft. This was made possible by contouring the collar elevations of diamond drill holes carefully. The drill holes are normally at 100-ft intervals on the surface and frequently at intervals of 50 ft. The

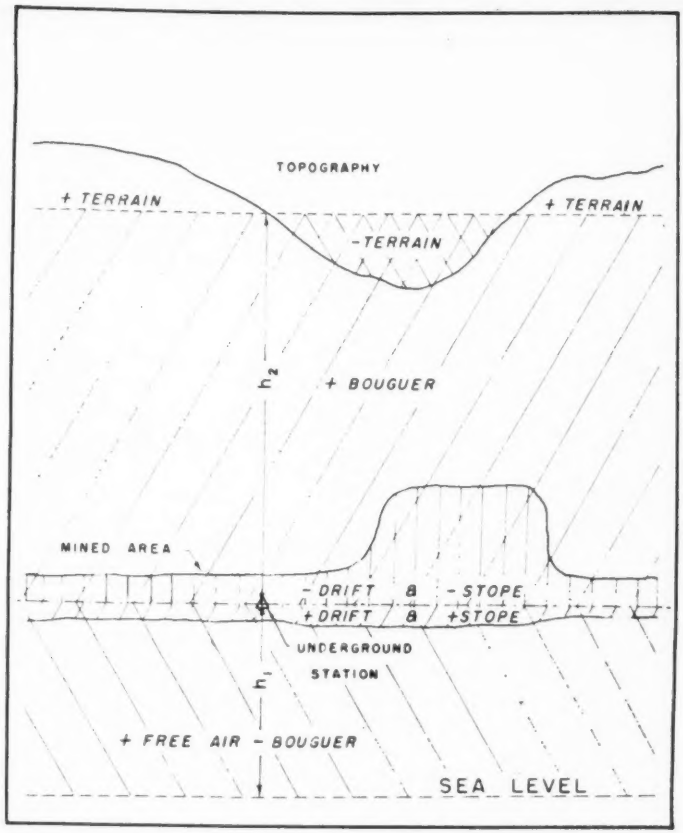

FIG. 4. Nature of the corrections applied to underground gravity observations.

corrections for surface topography were carried out using an extension of Hammer's terrain correction chart (1939) which was computed by Dr. Hammer in 1949 but not published. Corrections were computed for topography out to a radius of 8,578 ft from the station. Unlike terrain corrections for surface stations, errors in the calculation of terrain effects on underground stations are not cumulative, but tend to cancel, since mass above the level of the Bouguer slab is a positive correction, that below is negative.

An alternative method of correcting for the effect of material above an underground station is to compute the effect of all the mass above the underground station using only an extension of Hammer's terrain chart and not splitting the correction into a Bouguer correction for a slab of thickness h_2 plus a terrain correction for the remaining material. The "single correction method" is advantageous if considerable topographic relief or poor topographic control does not permit the accurate determination of h_2, since a large error in h_2 causes a correspondingly large error in the Bouguer correction for a slab of thickness h_2. The "single correction method" has the disadvantage that errors in estimating the topography using a terrain chart are cumulative, not positive and negative in sign as when the correction is split into a Bouguer correction plus terrain correction.

For mined-out areas below the elevation of an underground station in the mine, a positive stope or drift correction is applied. For mined-out areas above the level of an underground station, a negative correction is necessary. The computation of

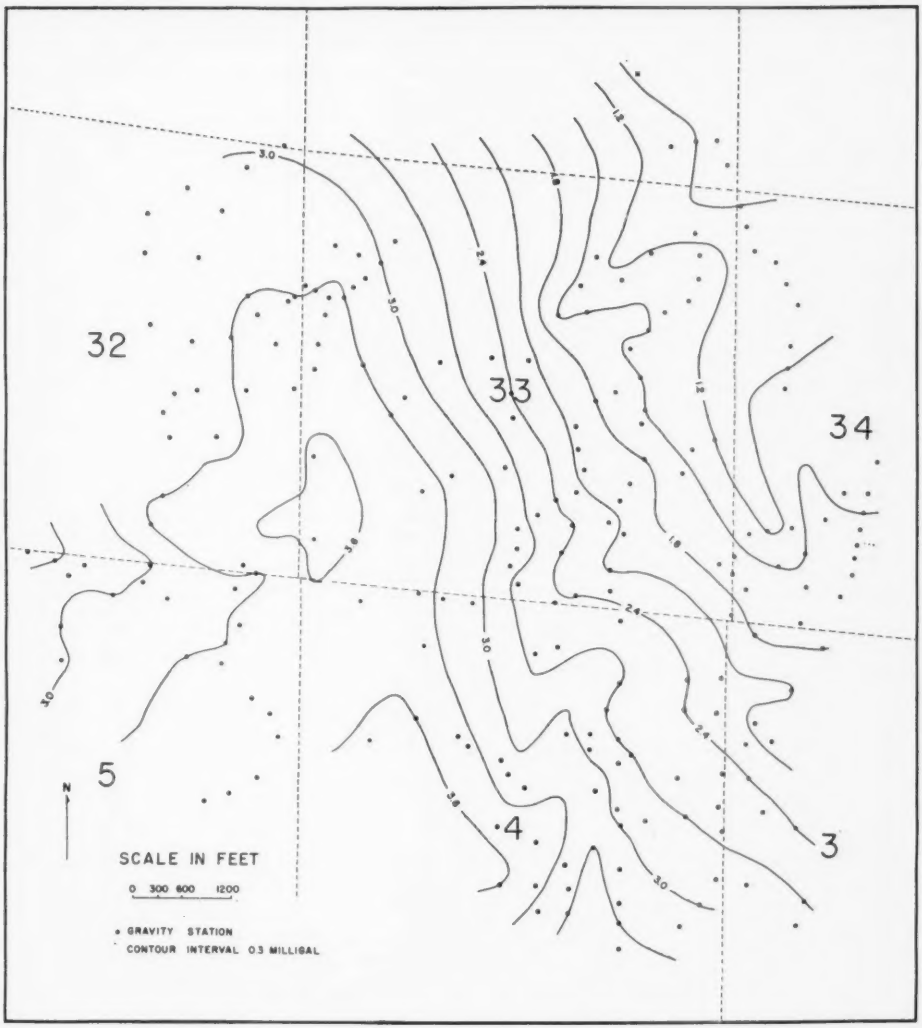

FIG. 5. Surface Bouguer gravity over the North Leadwood mine.

the correction for mine drifts is somewhat simplified by the fact that drifts have a more or less constant cross-section and one dimension, the length of the drift, which is much greater than either of the other two. Most of the stations were located in drifts of sufficient length so that their length could be considered infinite. This allowed the use of a "two-dimensional" theory of attraction. The correction for drifts was computed using a two-dimensional dot chart or graticule.

Corrections for mined-out areas of irregular shape such as stopes were made using Hammer's (1939) terrain correction charts. The gravity station was accurately located on an appropriate mine map. A terrain chart of the same scale was placed over the mine map and the number of compartments of the chart that fell within the stope and the average height of the stope within each compartment was estimated. The North Leadwood Mine maps show mine back and floor

elevations in the stopes at sufficiently close intervals that the corrections could be computed with an accuracy of .03 milligal for stopes 20 to 30 ft. high. However, the calculation of the correction is laborious and less accurate than the correction for drifts. For these reasons, stations were located in drifts whever possible. In the Leadwood Mine, there is, for the most part, only a single mining level. Stopes and drifts were essentially on the same level with the underground gravity stations. The corrections for mined-out areas were considerably smaller than if the mine had been multileveled, with stopes and drifts above and below gravity stations. A consideration of the corrections on the underground stations indicates that the underground observations are accurate to approximately 0.2 milligal. The contour interval of 0.3 milligal was used on the underground gravity map so that a direct comparison could be made with the surface survey. A density of 2.65 was used for the corrections for mined-out areas and a density of 2.60 used for the terrain corrections on the underground stations. Figure 6 is the Bouguer gravity map of the North Leadwood Mine observed underground in the Mine workings approximately 400 ft below the surface. The presence of the Leadwood and Schultz knobs is indicated by gravity highs of over a milligal. The anomalies over all the knobs are probably larger than shown by the map since gravity stations do not surround each knob to a great enough extent to outline the anomaly completely.

Many of the small gravity trends agree in general with the Lamotte sandstone contour map. Some of the smaller anomalies cannot be correlated exactly with what is known concerning structure, but they are believed to indicate areas favorable for additional prospecting. An example is the southern part of the Schultz knob or ridge. The gravity map indicates an extension of the Precambrian ridge to the south and southwest. This particular area has not been diamond drilled as thoroughly as many other parts of the mine. This south and southwest trend shown on the gravity map does not agree completely with the structure contour map of the Lamotte sandstone. The Lamotte sandstone map indicates a slightly southeast trend of the ridge.

The gravity nosing in the northern part of section 33 indicates a southward extension of the Switchback knob and a thinning of the Lamotte sandstone in this area. This area south of the Switchback knob has been little developed as is indicated by the absence of drifts along the crest of the gravity high.

Comparison of the surface and underground gravity map reveal several anomalies of interest. An example is the sharp gravity low on the surface map in the northeast corner of section five. This gravity low could be caused by the effect of mined-out area beneath it but calculations indicate that the stopes in this area are not sufficiently large to account for the entire gravity low. This feature appears as a gravity high on the underground gravity map. The most reasonable interpretation is that the anomaly is caused by a region of low density material above the underground station.

The Schultz fault has little, if any, gravity anomaly associated with it. At the southeast end of the fault there is a slight broadening of the gravity contours. The lack of a significant anomaly is possibly due to the transitional character of the density of the 19-bed of the Bonneterre formation, immediately above the Lamotte, and also, to the position of the gravity stations with respect to the fault. Many of the drifts crossing the faults are in the Lamotte sandstone on the upthrown (west) side of the fault. The drifts are inclined to the northeast so that, on crossing to the downthrown side of the fault, they again approach the top of the Lamotte sandstone. The gravity stations traversing the fault are therefore in the Lamotte sandstone on the upthrown side, largely nullifying any anomaly.

Comparison of the Lamotte sandstone contour map and the underground gravity map indicates that the sandstone contour closure over the Leadwood knob probably does not represent the exact position of the igneous knob. The gravity anomaly is offset 800 ft west of the Lamotte sandstone contour closure. The gravity anomaly corresponds more closely to the center of lead mineralization over the Leadwood knob than do the sandstone contours.

CONCLUSIONS

This survey indicates the information that can be obtained from a surface and underground gravity survey even in a mining district where the structural features are rather small and the density contrast low. Because of the closely

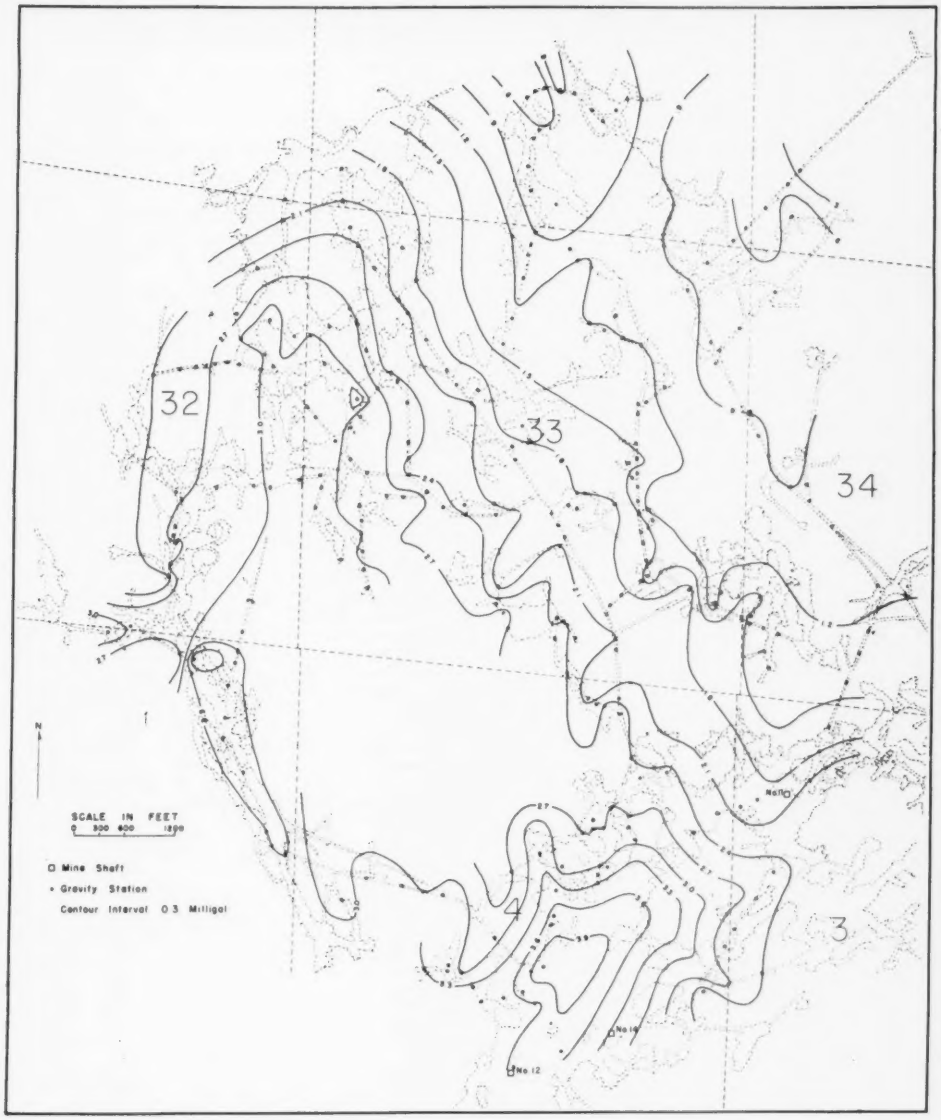

FIG. 6. Underground Bouguer gravity in the North Leadwood mine, showing mined areas.

spaced diamond drilling at Leadwood, the gravity map could be closely checked with the larger structures which were outlined years before by diamond drill holes. Both the surface and underground gravity maps revealed all the large structures associated with ore bodies at Leadwood. In addition, the underground gravity map indicated numerous small trends which may or may not be associated with ore deposition that can only be verified by further diamond drilling.

The two factors contributing the largest error to the underground gravity observations are

both the result of surface topography. These two factors are the vertical distance from the station to a point directly above it on the surface and estimation of terrain corrections from the available topographic maps. Because of closely spaced surface diamond drilling, the surface topography was known to greater accuracy than would be possible in most mining districts. Only in a region of very low surface relief or in a deeper mine could the accuracy of an underground survey be appreciably increased.

It is believed that in other mining districts that have not had the benefit of extensive diamond drilling, underground gravity surveys may offer a good reconnaissance tool for pinpointing areas of interest for drilling. An underground gravity survey in a deep mine has a very definite advantage over a surface survey since the accuracy of an underground survey increases as the effects of surface topography diminishes. Deeply buried ore bodies or structures may be below the resolution of a surface gravity survey over a deep mine.

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SOME ASPECTS OF ELASTIC WAVE PROPAGATION IN FLUID-SATURATED POROUS SOLIDS*

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Abstract: Biot's equations for the propagation of dilatational waves in fluid-saturated porous solids in the low-frequency range are analyzed for the purpose of application in geophysical research. The deformation constants of the system are unraveled in terms of compressibilities and porosity, and suitable approximate solutions for wave velocity and attenuation of the waves of both the first and the second kind are obtained. A saturated elastic porous solid is found to behave, as far as the wave of the first kind is concerned, approximately as a standard element. The wave of the second kind rapidly dies out with increasing distance from the source and consequently one might infer that in seismic studies only the wave of the first kind needs consideration. It is shown, however, that its presence has an effect upon the reflection and absorption at any interface between two different fluid-saturated porous solids. At such an interface a wave of the second kind is again generated. General formulae for the reflection and absorption for normal incidence at the interface are obtained, which include the effect of second-wave generation.

Additional results of the investigation are the following: A rather simple formula for the speed of sound in sedimentary rocks (the wave of the first kind) is obtained, which has to replace the so-called "time-average relation" now sometimes used. A comparison between the results obtained here and published results on wave propagation in simpler fluid-solid systems, such as, for instance, suspensions, showed some weak points in the older theories. Suggestions for possible improvements are given.

LIST OF SYMBOLS

$b = \mu\phi^2/k$

c_b = bulk compressibility

c_l = fluid compressibility

c_r = matrix compressibility

E = energy flux per cycle

e = absolute dilatation of bulk material

G, H, K, L, P, S, Q, R = elastic deformation constants

G_b = shear modulus of bulk material

k = permeability

l = propagation constant

p = fluid tension

q = quality factor

t = time

u = absolute displacement of bulk material normal to interface

V = wave velocity (with index 0 for zero frequency); (with index ∞ for infinitely large frequency (abstract theoretical values))

w = relative displacement of fluid material normal to interface

x = distance travelled

ϕ = porosity

α = absorption coefficient

$\beta = c_r/c_b$

δ = logarithmic decrement

ϵ = absolute dilatation of pore fluid

ζ = relative dilatation between solid and fluid

λ = wave length

μ = fluid viscosity

ν = Poisson's ratio

ρ = density (the indices 11, 12 and 22 correspond with those of the Biot

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theory)
$\bar{\sigma}$ = hydrostatic stress component in bulk material
ω = angular frequency
ω_c = characteristic angular frequency = $\mu/k\rho$
∇ = Laplace operator

A general theory of three-dimensional propagation of elastic waves in a fluid-saturated porous solid was presented by Biot (1956a). Since the development of this wave propagation theory it has been known that in a fluid-solid system, provided both solid and fluid consist of a continuüm, two entirely different, coupled, dilatational waves are generated at a sound source.

The basic equations describing such dilatational waves in a fluid-saturated porous structure, which on a macroscopic scale can be considered as isotropic and elastic, are according to Biot

$$\nabla^2\{(P+S)e+Q\epsilon\} = \frac{\partial^2}{\partial t^2}(\rho_{11}e+\rho_{12}\epsilon)+\frac{\mu\phi^2}{k}\frac{\partial}{\partial t}(e-\epsilon),$$

$$\nabla^2\{Qe+R\epsilon\} = \frac{\partial^2}{\partial t^2}(\rho_{12}e+\rho_{22}\epsilon)-\frac{\mu\phi^2}{k}\frac{\partial}{\partial t}(e-\epsilon). \quad (1)$$

In this set of simultaneous differential equations e represents the absolute dilatation of the solid and ϵ that of the fluid. For the meaning of the various symbols the reader is referred to the list at the beginning of the paper. The restrictions on the validity of these equations are further: The wave length has to be appreciably larger than the largest dimension of the grains of which the porous structure is built up, and relative movement between fluid and solid frame has to take place according to Darcy's law of fluid flow through porous media. Also it is assumed that the effect of temperature variations due to dissipation of energy can be neglected.

The scope of the present investigation is to present a more detailed analysis of the implications of equation (1) for wave propagation analysis in sedimentary rocks.

To this end it appears to be more suitable to replace ϵ by another dependent variable, the relative dilatation between solid and fluid

$$\zeta = \phi(e-\epsilon).$$

This variable also has already been introduced by Biot in another publication (Biot 1956b). The use of the dilatations e and ζ instead of e and ϵ as dependent variables in equation (1) leads, after some rearrangements, to

$$\left.\begin{aligned}\nabla^2(He-K\zeta) &= \frac{\partial^2}{\partial t^2}(\rho e-\rho_l\zeta),\\ \nabla^2(Ke-L\zeta) &= \frac{\partial^2}{\partial t^2}(\rho_l e-\rho_c\zeta)-\frac{\mu}{k}\frac{\partial\zeta}{\partial t}\end{aligned}\right\}, \quad (1a)$$

in which $H=P+S+2Q+R$, (2)

$$K=\frac{Q+R}{\phi}, \quad (3)$$

$$L=\frac{R}{\phi^2}, \quad (4)$$

$$\rho=\rho_{11}+2\rho_{12}+\rho_{22}, \quad (5)$$

$$\rho_l=\frac{\rho_{12}+\rho_{22}}{\phi} \quad (6) \quad \text{and} \quad \rho_c=\frac{\rho_{22}}{\phi^2}. \quad (7)$$

The stress-strain relations are

$$\bar{\sigma}=\left(H-\frac{4}{3}G\right)e-K\zeta, \quad (8)$$

$$p=Ke-L\zeta. \quad (9)$$

In the latter relationships $\bar{\sigma}$ is the "true" hydrostatic stress acting on the solid skeleton and p the hydrostatic tension in the fluid phase. The difference between $\bar{\sigma}$ and p is the "effective stress," well-known in soil mechanics.

P, S, Q and R, or G, H, K and L are elastic constants of the system. From earlier work (Geertsma 1957) it is known that without fluid compressibility effects for a macroscopically isotropic, homogeneous porous structure we may also write

$$e=-(c_b-c_r)p+c_b\bar{\sigma} \quad (10)$$

and

$$\zeta=-\{c_b-(1+\phi)c_r\}p+(c_b-c_r)\bar{\sigma}. \quad (11)$$

If we include the compressibility of the fluid pres-

ent in the pores in the expression for ζ, equation (11) changes into

$$\zeta = -\{c_b - (1+\phi)c_r + \phi c_l\}p + (c_b - c_r)\bar{\sigma}, \tag{12}$$

while equation (10) remains the same. Thus, according to (10) and (12) the stress-strain relations are also given by

$$\bar{\sigma} = \left[\frac{(1-\beta)^2}{(1-\phi-\beta)c_r + \phi c_l} + \frac{\beta}{c_r}\right]e - \frac{1-\beta}{(1-\phi-\beta)c_r + \phi c_l}\zeta, \tag{8a}$$

$$p = \frac{1-\beta}{(1-\phi-\beta)c_r + \phi c_l}e - \frac{1}{(1-\phi-\beta)c_r + \phi c_l}\zeta, \tag{9a}$$

where the abbrevation $\beta = c_r/c_b$ is introduced.

This notation (8a) and (9a) has the advantage that the deformation properties of the system are now expressed in terms of compressibilities c_b, c_r and c_l and the porosity ϕ, which are familiar properties of a porous system. Comparison between the two sets of stress-strain relation leads to

$$H = \frac{(1-\beta)^2}{(1-\phi-\beta)c_r + \phi c_l} + \left(\frac{\beta}{c_r} + \frac{4}{3}G_b\right), \tag{13}$$

$$K = \frac{1-\beta}{(1-\phi-\beta)c_r + \phi c_l}, \tag{14}$$

and

$$L = \frac{1}{(1-\phi-\beta)c_r + \phi c_l}. \tag{15}$$

As

$$\left(\frac{\beta}{c_r} + \frac{4}{3}G_b\right)$$

can be replaced by

$$\frac{3}{c_b}\left(\frac{1-\nu_b}{1+\nu_b}\right),$$

where ν represents Poisson's ratio, one gets from an average value of $\nu = 0.2$ for rocks:

$$\left(\frac{\beta}{c_r} + \frac{4}{3}G_b\right) \approx 2\frac{\beta}{c_r}.$$

It is of importance to note that from equations (8) and (9) or (10) and (12) the four "Maxwell-relations" for the porous system are easily derived:

$$= \left(\frac{\partial p}{\partial e}\right)_\zeta = -\left(\frac{\partial \sigma}{\partial \zeta}\right)_e = K = \frac{1-\beta}{(1-\phi-\beta)c_r + \phi c_l}, \tag{16}$$

$$\left(\frac{\partial \bar{\sigma}}{\partial p}\right)_e = \left(\frac{\partial \zeta}{\partial e}\right)_p = (1-\beta), \tag{17}$$

$$\left(\frac{\partial \zeta}{\partial \bar{\sigma}}\right)_p = -\left(\frac{\partial e}{\partial p}\right)_{\bar{\sigma}} = c_b(1-\beta), \tag{18}$$

$$\left(\frac{\partial p}{\partial \bar{\sigma}}\right)_\zeta = \left(\frac{\partial e}{\partial \zeta}\right)_{\bar{\sigma}} = \frac{1-\beta}{1-(1+\phi)\beta + \phi\dfrac{c_l}{c_b}}. \tag{19}$$

Relation (18) is the Betti-Raleigh reciprocal relationship used by Geertsma (1957) to arrive at (10) and (11).

The frequency equation

If we now turn to propagation of a plane dilatational wave of the form

$$e = C_1 \exp[j(\omega t - lx)],$$
$$\zeta = C_2 \exp[j(\omega t - lx)],$$

the equations (1a) after substitution of e and ζ provide the frequency equation

$$\begin{vmatrix} (z-1) & (\gamma_l - z\sigma_K) \\ (\gamma_l - z\sigma_K) & \left(\sigma_L z - \gamma_e + j\dfrac{\omega_c}{\omega}\right) \end{vmatrix} = 0. \tag{20}$$

Here z is introduced as a variable defined by

$$z = V_c^2\frac{l^2}{\omega^2}, \quad \text{where } V_c^2 = \frac{H}{\rho}.$$

For the sake of shortness the dimensionless ratios

$$\gamma_l = \frac{\rho_l}{\rho}, \quad \gamma_c = \frac{\rho_c}{\rho}, \quad \sigma_K = \frac{K}{H}, \quad \sigma_L = \frac{L}{H}$$

and

$$\frac{\omega_c}{\omega} = \frac{\mu}{k\rho\omega}$$

are introduced.

Approximate solutions of the frequency equation

From

$$\mathrm{Re}\,(z) + j\,\mathrm{Im}\,(z) = [\mathrm{Re}\,(l) + j\,\mathrm{Im}\,(l)]^2 \frac{V_c^2}{\omega^2}$$

it follows that

$$\frac{\mathrm{Im}\,(z)}{\mathrm{Re}\,(z)} = \frac{4q}{1 - 4q^2}, \tag{21}$$

where

$$q = \text{quality factor} = \frac{\pi}{\delta} = -\frac{\pi}{\lambda\,\mathrm{Im}\,(l)} = -\frac{1}{2}\frac{\mathrm{Re}\,(l)}{\mathrm{Im}\,(l)}.$$

From

$$\mathrm{Re}\,(z) = [\mathrm{Re}^2\,(l) - \mathrm{Im}^2\,(l)]\frac{V_c^2}{\omega^2}$$

one derives that

$$V^2 = V_c^2 \frac{4q^2 - 1}{4q^2\,\mathrm{Re}\,(z)}. \tag{22}$$

δ is the logarithmic decrement, which in turn is equal to the product of wavelength λ and attenuation coefficient $-Im(l)$. From the relations (21) and (22) one concludes that for not too small values of the quality factor, say $q>5$, which already represents an enormous damping, the approximate relations

$$\frac{\mathrm{Im}\,(z)}{\mathrm{Re}\,(z)} \approx -\frac{1}{q} \tag{21a}$$

and

$$V^2 \approx \frac{V_c^2}{\mathrm{Re}\,(z)} \tag{22a}$$

will hold.

The frequency equation (20) is further of the type

$$a^2z^2 - bz + 1 = 0.$$

The solution of this equation is well known:

$$z_{1,2} = \frac{1}{a}\left(\frac{b}{2a} \mp \sqrt{\frac{b^2}{4a^2} - 1}\right).$$

The solution with the $-$ sign gives the propagation properties of the wave of the first kind and that with the $+$ sign those of the wave of the second kind.

Fortunately it can be shown that for most porous rocks $b/2a \gg 1$. As long as this is the case, approximate solutions for z are given by

$$z_1 \approx \frac{1}{b} \quad \text{and} \quad z_2 \approx \frac{b}{a^2}$$

(compare with de Josselin de Jong (1956)). This solution leads immediately to the following values for z:

$$z_1 \approx \frac{(\gamma_c - \gamma_l{}^2) - j\,\dfrac{\omega_c}{\omega}}{(\gamma_c + \sigma_L - 2\gamma_l\sigma_K) - j\,\dfrac{\omega_c}{\omega}}, \tag{23}$$

$$z_2 \approx \frac{(\gamma_c + \sigma_L - 2\gamma_l\sigma_K) - j\,\dfrac{\omega_c}{\omega}}{\sigma_L - \sigma_K{}^2}. \tag{24}$$

For the first plane dilatational wave the condition $q>5$ is certainly fulfilled and the approximate relations (21a) and (22a) hold. Therefore,

$$V_1{}^2 \approx \frac{H}{\rho} \cdot \frac{(\gamma_c + \sigma_L - 2\gamma_l\sigma_K)^2 + \left(\dfrac{\omega_c}{\omega}\right)^2}{(\gamma_c - \gamma_l{}^2)(\gamma_c + \sigma_L - 2\gamma_l\sigma_K) + \left(\dfrac{\omega_c}{\omega}\right)^2} \tag{25}$$

and

$$\frac{1}{q_1} \approx \frac{\frac{\omega_c}{\omega}(\gamma_l^2+\sigma_L-2\gamma_l\sigma_K)}{(\gamma_c-\gamma_l^2)(\gamma_c+\sigma_L-2\gamma_l\sigma_K)+\left(\frac{\omega_c}{\omega}\right)^2}. \tag{26}$$

From equation (25) it is easily seen that for $\omega \to 0$

$$V_{10}^2 = \frac{H}{\rho} \tag{27}$$

while for $\omega \to \infty$

$$V_{1\infty}^2 = \frac{H}{\rho}\cdot\frac{\gamma_c+\sigma_L-2\gamma_l\sigma_K}{\gamma_c-\gamma_l^2} = \frac{L\rho+H\rho_c-2\rho_l K}{\rho\rho_c-\rho_l^2}. \tag{28}$$

Thus it appears possible to rewrite equation (25) in the form

$$V_1^2 \approx \frac{V_{1\infty}^4+V_{10}^4\left(\frac{\omega_c}{A\omega}\right)^2}{V_{1\infty}^2+V_{10}^2\left(\frac{\omega_c}{A\omega}\right)^2} \tag{25a}$$

if

$$A = \gamma_c-\gamma_l^2 = \frac{\rho\rho_c-\rho_l^2}{\rho^2}$$

while furthermore

$$\frac{\delta_1}{\pi} = \frac{1}{q_1} \approx \frac{V_{1\infty}^2/V_{10}^2-1}{\left(\frac{\omega_c}{A\omega}\right)+\left(\frac{\omega A}{\omega_c}\right)V_{1\infty}^2/V_{10}^2}. \tag{26a}$$

From these equations (25a) and (26a) it follows that the behavior of the material as far as the wave of the first kind is concerned is very similar to that of a standard-element, i.e. an auxiliary spring in parallel with a Maxwell-element. This result is not too surprising as Freudenthal's treatment of "homogeneous relaxation" in the Encyclopedia of Physics (Freudenthal 1958), under which heading the behavior of the wave of the first kind can be classified, leads to a description by a standard element too.

The same procedure cannot be followed for the wave of the second kind, as here in general the damping is very large. However, as long as

$$\omega/\omega_c \ll 1:$$

$$z_2 \approx j\frac{-\omega_c/\omega}{\sigma_L-\sigma_K^2}.$$

This leads to

$$V_2 = \sqrt{\frac{2(LH-K^2)}{\rho H}\frac{\omega}{\omega_c}}, \tag{29}$$

and

$$q_2 = \tfrac{1}{2} \quad \text{or} \quad \delta_2 = 2\pi. \tag{30}$$

This value of q_2 (and δ_2) means that on the right-hand side of equation (1) the second terms are dominating and the solution of the wave equation degenerates to that of a diffusion equation.

This corresponds with results already obtained earlier by Biot (1956a) and also with de Josselin de Jong's equation for the second dilatational wave (de Josselin de Jong, 1956).

Comparison with earlier theoretical results

The results obtained above can be considered as a generalization of those of other investigators on the theory of wave propagation in two-phase systems. Most of the published work is related to *suspensions*. In such systems the compressibility $c_b=\infty$ and $G_b=0$. Thus, $\beta=0$, and accordingly

$$H = K = L = \frac{1}{(1-\phi)c_r+\phi c_l}.$$

Furthermore, no attention has in general been paid to mass coupling effects; for comparison with these studies we will therefore also put $\rho_{12}=0$.

Under these conditions there is only one dilatational wave, as $LH-K^2=0$. In equation (25a) we now have

$$V_0^2 = \frac{H}{\rho} = \frac{1}{[(1-\phi)c_r+\phi c_l][(1-\phi)\rho_r+\phi\rho_l]} \tag{27s}$$

and

$$V_\infty^2 = \frac{L\rho + H\rho_c - 2\rho_l K}{\rho\rho_c - \rho_l^2}$$

$$= \frac{\dfrac{\phi}{\rho_l} + \dfrac{(1-\phi)}{\rho_r}}{(1-\phi)c_r + \phi c_l}, \tag{28s}$$

while

$$A = \frac{\rho_l\rho_r}{[\rho_r(1-\phi) + \rho_l\phi]^2} \cdot \frac{1-\phi}{\phi}.$$

Equation (27s) is Wood's formula (Wood 1941) for the speed of (dilatational) waves in suspensions. Whether Wood's formula or equation (28s) has to be used for a suspension depends clearly on the frequency applied, or, more exactly, on the value of $A\omega/\omega_c$. As the latter depends on porosity, which corresponds to one minus concentration in suspensions, Wood's formula is valid only at such low frequencies that for all concentrations investigated the value of $A\omega/\omega_c$ is very small compared to unity.

The mobility, which occurs in the expression for ω_c, is rather difficult to estimate for suspensions. Perhaps it is most convenient to derive this mobility from low-frequency measurements of the damping. According to equation (26a) for low values of $A\omega/\omega_c$

$$\frac{1}{q} = \frac{\omega}{\omega_c} \cdot \frac{(1-\phi)}{\phi\rho} \cdot \left[\rho_r\phi + \rho_l(1-\phi) - \frac{\rho_r\rho_l}{\rho}\right]. \tag{31}$$

The applicability of this formula depends on whether mass-coupling effects in suspensions can be neglected or not. It is beyond the scope of this investigation to discuss this point.

Ament (1953) presents a formula for the speed of sound in porous media, which turns out to be equivalent with the above results. Ament's notation reads:

$$\frac{\omega^2}{l^2} = \frac{1}{c^x\rho^x},$$

where c^x is the "effective compressibility" and ρ^x the "effective density." c^x is taken equal to $c_r(1-\phi)+c_l\phi$ and the effective density is thus ρz. From the suspension-theory developed above we derive

$$\rho z = \rho - \frac{j\omega \dfrac{k}{\mu}\phi(1-\phi)^2(\rho_r-\rho_l)^2}{\phi + j\omega \dfrac{k}{\mu}(1-\phi)\{\rho_l + \phi(\rho_r-\rho_l)\}}. \tag{32}$$

This is the same result as obtained by Ament, though comparison requires a change in notation.[1] Ament's notation is more general in one respect, since it allows for taking into account a more general flow equation for the continuous fluid phase than used in the present treatment. The reason that the present study has been restricted to a Darcy type of fluid motion is that in the porous sediments usually encountered the value of $A\omega/\omega_c$ remains rather small, even for the large values of the frequency used in velocity logs, owing to low fluid mobility values. This, however, does not always hold for suspensions.

That Ament's treatment failed to explain elastic wave propagation in compacted ocean sediments, was shown by Laughton (1957). For such media it is not allowed to take $c_b = \infty$. However, here the matrix material may be considered as incompressible, so $c_r = 0$. This assumption is also a very familiar one in the theory of clay consolidation. The elastic constants for this particular case read:

$$K = L = \frac{1}{\phi c_l},$$

while, if it is further assumed that for clay-type sediments Poisson's ratio of the skeleton $\nu_b = \frac{1}{2}$, we can moreover write

$$H = \frac{1}{\phi c_l} + \frac{1}{c_b}.$$

For this situation we have

$$V_{10}^2 = \frac{1}{\rho c_b} + \frac{1}{\phi\rho c_l}, \tag{33}$$

which is identical with Laughton's velocity formula. The expression

[1] Ament's filter permeability H equals $-(k/\mu)$ here.

$$\frac{\phi c_l + c_b}{\phi c_l c_b}$$

is Laughton's "structure bulk modulus." The derivation of the corresponding values of $V_{1\infty}^2$ and $1/q_{10}$ is left to the reader.

Gassmann's "compressibility of a porous closed system" (Gassmann 1951) results from the present theory, if one considers three-dimensional instead of plane dilatational waves, since for this case it is found that $1/H$ is replaced by

$$\frac{c_b\phi(c_l - c_r) + c_r(c_b - c_r)}{\phi(c_l - c_r) + (c_b - c_r)}. \tag{34}$$

This is identical with van der Knaap's expression for this compressibility (van der Knaap, 1959).

In the literature on sound absorbing materials the rigid frame theory is extensively treated (Zwikker and Kosten 1949, Morse 1952). The assumption of a rigid skeleton means that we must put in the general theory $c_r = c_b = 0$ and $\beta = 1$. This implies that

$$H = \infty, \qquad K = 0, \qquad L = \frac{1}{\phi c_l}.$$

Of the basic equations (1) only the second, related to the movement of the fluid, is now significant. As for a rigid frame $e = 0$, we obtain for this particular case

$$\frac{1}{c_l}\nabla^2\epsilon = \phi\rho_c\frac{\partial^2\epsilon}{\partial t^2} + \frac{\mu\phi}{k}\frac{\partial\epsilon}{\partial t}.$$

This leads immediately to

$$\frac{\omega^2}{l^2} = \frac{1}{\phi\rho_c c_l}\left(\frac{1}{1 - j\dfrac{\omega_c}{\omega}\dfrac{\rho}{\rho_c}}\right).$$

There is only one plane dilatational wave, but contrary to the cases treated above this is now the second wave. Its wave velocity and attenuation for small values of ω/ω_c:

$$V_2 = \sqrt{\frac{2}{\rho\phi c_l}\frac{\omega}{\omega_c}} \quad \text{and} \quad q_2 = \frac{1}{2}, \tag{35}$$

follow from the equation for ϵ, but also from equation (29), after insertion of the appropriate values for the elastic constants. These relations are equivalent with formulae obtained by Zwikker and Kosten and by Morse. From this it follows that the sound absorption of porous walls is based primarily on the properties of what we have indicated as the wave of the second kind. As a result it must be concluded that at low values of ω/ω_c the damping of materials such as acoustic plasters, wood fibre and the like is satisfactorily described by a diffusion type equation.

The influence of the wave of the second kind on reflection at the interface between dissimilar fluid saturated porous media

Though in porous rocks the wave of the second kind can hardly be detected at some distance from the wave source, its existence cannot be entirely overlooked, as it must lead to absorption of a part of the total input energy. It has also been shown above that the wave of the second kind is the main cause of sound absorption by rigid porous walls. This suggests that a wave of the second kind is not only generated at a wave source, but also at any interface between dissimilar fluid-containing rocks. One is strengthened in this belief by Lessen's work in a closely related field of research, viz. the behavior of thermoelastic waves in solids at an interface (Lessen (1956)). Lessen states: "If it is considered that the incident wave is of one family (that is, if the interface is far away from the source), then it is necessary, in order to satisfy the boundary conditions at the interface, that the reflected waves be of both families and the refracted waves be of both families" (Lessen, Loc. cit.). For this reason the propagation through the normal interface between dissimilar fluid-saturated porous rocks of plane dilatational waves needs examining. This will elucidate the role of the wave of the second kind in some more detail.

We shall assume two different semi-infinite porous fluid-saturated media, in contact with each other, and indicate the wave properties of the second medium with an accent. The two media have a common interface at $x = 0$. The source is situated in the first medium and here there will be an incident and a reflected wave. In terms of displacements one obtains for the solid

$$u_i = A_{1i}\exp j(\omega t - l_1 x) + A_{2i}\exp j(\omega t - l_2 x), \tag{36}$$

$$u_r = A_{1r} \exp j(\omega t + l_1 x) + A_{2r} \exp j(\omega t + l_2 x), \tag{37}$$

and for the relative displacement of the fluid

$$w_i = B_{1i} \exp j(\omega t - l_1 x) + B_{2i} \exp j(\omega t - l_2 x), \tag{38}$$

$$w_r = B_{1r} \exp j(\omega t + l_1 x) + B_{2r} \exp j(\omega t + l_2 x). \tag{39}$$

In the second medium we have a sum of waves penetrating into it:

$$u' = A_1' \exp j(\omega t - l_1' x) + A_2' \exp j(\omega t - l_2' x), \tag{40}$$

$$w' = B_1' \exp j(\omega t - l_1' x) + B_2' \exp j(\omega t - l_2' x). \tag{41}$$

The indices 1 and 2 indicate the waves of the first and the second kind, respectively.

The corresponding dilatations follow from

$$e = \frac{\partial u}{\partial x} \quad \text{and} \quad \zeta = \frac{\partial w}{\partial x}$$

$$\left(\frac{\partial w}{\partial t} = v_x = \text{fluid velocity in the pores}\right).$$

So

$$e_i = -jl_1 A_{1i} \exp j(\omega t - l_1 x) - jl_2 A_{2i} \exp j(\omega t - l_2 x), \tag{42}$$

$$e_r = +jl_1 A_{1r} \exp j(\omega t + l_1 x) + jl_2 A_{2r} \exp j(\omega t + l_2 x), \tag{43}$$

$$e' = -jl_1' A_1' \exp j(\omega t - l_1' x) - jl_2' A_2' \exp j(\omega t - l_2' x), \tag{44}$$

$$\zeta_i = -jl_1 B_{1i} \exp j(\omega t - l_1 x) - jl_2 B_{2i} \exp j(\omega t - l_2 x), \tag{45}$$

$$\zeta_r = +jl_1 B_{1r} \exp j(\omega t + l_1 x) + jl_2 B_{2r} \exp j(\omega t + l_2 x), \tag{46}$$

$$\zeta' = -jl_1' B_1' \exp j(\omega t - l_1' x) - jl_2' B_2' \exp j(\omega t - l_2' x). \tag{47}$$

In this way 12 unknown amplitudes A and B or 11 unknown amplitude ratios are obtained. So 11 equations are required to find these amplitude ratios. Six of these equations can be derived from the wave equations (1a) themselves. They are

$$\frac{B_{1i}}{A_{1i}} = \frac{B_{1r}}{A_{1r}} = \frac{H(z_1 - 1)}{z_1 K - \frac{\rho_l}{\rho} H} = m_1, \tag{48}$$

$$\frac{B_{2i}}{A_{2i}} = \frac{B_{2r}}{A_{2r}} = \frac{H(z_2 - 1)}{z_2 K - \frac{\rho_l}{\rho} H} = m_2, \tag{49}$$

$$\frac{B_1'}{A_1'} = \frac{H'(z_1' - 1)}{z_1' K' - \frac{\rho_l'}{\rho'} H'} = m_1', \tag{50}$$

$$\frac{B_2'}{A_2'} = \frac{H'(z_2' - 1)}{z_2' K' - \frac{\rho_l'}{\rho'} H'} = m_2'. \tag{51}$$

The initial condition depends strongly on the way of loading at the source, but if x_0 indicates the distance between wave source and the interface we know that the ratio A_{2i}/A_{1i} decays proportional to

$$\exp[x_0\{\text{Im}\,(-l_1) - \text{Im}\,(-l_2)\}]. \tag{52}$$

The four remaining equations are obtained by the boundary conditions at $x=0$:

a. for the solid displacement

$$u_1 + u_2 = u = u'; \tag{53}$$

b. for the relative fluid displacement

$$w_1 + w_2 = w = w'; \tag{54}$$

c. for the normal solid stress

$$\bar{\sigma}_x = \bar{\sigma}_x'; \tag{55}$$

d. for the fluid pressures

$$p = p'. \tag{56}$$

Capillary pressure differences are neglected. From these boundary conditions it follows that at $x=0$

$$(A_{1i} + A_{1r}) + (A_{2i} + A_{2r}) = A_1' + A_2',$$

$$(B_{1i} + B_{1r}) + (B_{2i} + B_{2r}) = B_1' + B_2',$$

$$K\{l_1(B_{1i} - B_{1r}) + l_2(B_{2i} - B_{2r})\} - H\{l_1(A_{1i} - A_{1r}) + l_2(A_{2i} - A_{2r})\}$$

$$= K'(l_1'B_1' + l_2'B_2') - H'(l_1'A_1' + l_2'A_2'),$$

$$L\{l_1(B_{1i} - B_{1r}) + l_2(B_{2i} - B_{2r})\}$$
$$- K\{l_1(A_{1i} - A_{1r}) + l_2(A_{2i} - A_{2r})\}$$
$$= L'(l_1'B_1' + l_2'B_2') - K'(l_1'A_1' + l_2'A_2').$$

After introduction of the relations (48) through (51) one obtains the equations in terms of A's only:

$$(57)\quad (A_{1i} + A_{1r}) + (A_{2i} + A_{2r}) = A_1' + A_2',$$

$$(58)\quad m_1(A_{1i} + A_{1r}) + m_2(A_{2i} + A_{2r}) = m_1'A_1' + m_2'A_2',$$

$$(59)\quad \begin{aligned} &K\{l_1m_1(A_{1i} - A_{1r}) + l_2m_2(A_{2i} - A_{2r})\} \\ &- H\{l_1(A_{1i} - A_{1r}) + l_2(A_{2i} - A_{2r})\} \\ &= K'(l_1'm_1'A_1' + l_2'm_2'A_2') \\ &- H'(l_1'A_1' + l_2'A_2'), \end{aligned}$$

$$(60)\quad \begin{aligned} &L\{l_1m_1(A_{1i} - A_{1r}) + l_2m_2(A_{2i} - A_{2r})\} \\ &- K\{l_1(A_{1i} - A_{1r}) + l_2(A_{2i} - A_{2r})\} \\ &= L'(l_1'm_1'A_1' + l_2'm_2'A_2') \\ &- K'(l_1'A_1' + l_2'A_2'). \end{aligned}$$

For values of ω/ω_c much smaller than unity, for which the theory is best suited, we know already that to a first approximation

So for this situation one obtains

$$m_1 \approx m_1' \approx 0, \tag{61}$$

$$\left.\begin{aligned} m_2 &\approx \frac{H}{K} \\ m_2' &= \frac{H'}{K'} \end{aligned}\right\}. \tag{62}$$

Furthermore,

$$l_1 \approx \omega\sqrt{\frac{\rho}{H}} \tag{63}$$

and

$$l_2 \approx (1 - j)\omega\sqrt{\frac{\rho H}{2(LH - K^2)}\,\frac{\omega_c}{\omega}}. \tag{64}$$

The introduction of (61) and (62) reduces the amplitude equations to

$$(A_{1i} + A_{1r}) + (A_{2i} + A_{2r}) = A_1' + A_2',$$
$$HK'(A_{2i} + A_{2r}) = H'KA_2',$$
$$l_1H(A_{1i} - A_{1r}) = H'l_1'A_1',$$
$$l_2(LH - K^2)(A_{2i} - A_{2r}) - K^2l_1(A_{1i} - A_{1r})$$
$$= l_2'(L'H' - K'^2)A_2' - K'^2l_1'A_1'.$$

From this we derive that

$$2A_{1i} = \left(1 + \frac{H'}{H}\,\frac{l_1'}{l_1}\right)A_1' + \left(1 - \frac{H'K}{HK'}\right)A_2', \tag{65}$$

$$2A_{1r} = \left(1 - \frac{H'}{H}\,\frac{l_1'}{l_1}\right)A_1' + \left(1 - \frac{H'K}{HK'}\right)A_2', \tag{66}$$

$$2A_{2i} = \frac{\dfrac{K'}{K}\,\dfrac{l_1'}{l_2}\left(1 - \dfrac{H'K}{HK'}\right)}{\left(1 - \dfrac{LH}{K^2}\right)}A_1' + \left[\frac{\dfrac{K'}{K}\,\dfrac{l_2'}{l_2}\left(1 - \dfrac{L'H'}{K'^2}\right)}{\left(1 - \dfrac{LH}{K^2}\right)} + \frac{H'K}{HK'}\right]A_2', \tag{67}$$

$$2A_{2r} = -2A_{2i} + 2\,\frac{H'K}{HK'}\,A_2'. \tag{68}$$

$$z_1 = 1$$

and

$$z_2 = -j\,\frac{\omega_c/\omega}{\sigma_L - \sigma_K^2}.$$

The set of equations (65) through (68) together with the initial condition is the complete answer of our reflection problem. However, it is common practice to express the result in absorption or reflection coefficients instead of amplitude equations.

Determination of absorption coefficients

The potential energy per unit volume of the system is given by

$$\bar{\sigma}e - p\zeta, \tag{69}$$

and the potential energy flux is

$$(\bar{\sigma}e - p\zeta)V. \tag{70}$$

The energy flux per cycle thus amounts to

$$E = \int_t^{t+2\pi/\omega} (\bar{\sigma}e - p\zeta)V\,dt. \tag{71}$$

With $u = A \exp j(\omega t - lx)$ and $w = B \exp j(\omega t - lx)$ the real value of the energy flux per cycle (E) is given by

$$\pi \operatorname{Re}(l) \mid A \mid^2 [H - 2K \operatorname{Re}(m) + L \mid m^2 \mid]. \tag{72}$$

Approximately, for the waves of the first kind $m_1 = m_1' = 0$, so

$$E_1 \approx \pi\omega \sqrt{\rho H} \mid A_1 \mid^2, \tag{73}$$

while for the waves of the second kind $m_2 = H/K$, and accordingly

$$E_2 \approx \pi\omega \frac{H}{K^2} \cdot \sqrt{\frac{1}{2}\rho H(LH - K^2)\frac{\omega_c}{\omega}} \mid A_2 \mid^2. \tag{74}$$

The values of $|A_1|^2$ and $|A_2|^2$ can be derived from equations (65) through (68). The results obtained can thus be expressed in terms of an absorption coefficient, defined as the ratio of energy flux T penetrating into the second medium and incident energy flux E_I. For small values of ω/ω_c and a source at not too small a distance from the interface ($A_{2i}/A_{1i} \approx 0$) it follows that

$$E_I = \pi\omega \sqrt{\rho H} \mid A_{1i} \mid^2,$$

$$E_{T_1} = \pi\omega \sqrt{\rho' H'} \mid A_1' \mid^2,$$

$$E_{T_2} = \pi\omega \frac{H'}{K'^2} \cdot \sqrt{\frac{1}{2}\rho' H'(L'H' - K'^2)\frac{\omega_c'}{\omega}} \mid A_2' \mid^2.$$

The absorption coefficient is defined by

$$\alpha = \frac{E_{T_1} + E_{T_2}}{E_I}.$$

So

$$\alpha = \sqrt{\frac{\rho' H'}{\rho H}} \frac{\mid A_1' \mid^2 + \frac{H'}{K'^2}\sqrt{\frac{L'H' - K'^2}{2}\frac{\omega_c'}{\omega}} \mid A_2' \mid^2}{\mid A_{1i} \mid^2}. \tag{75}$$

From some special cases the solution can readily be given in a closed form. Examples are

a. the solid-against-solid case;
b. the impermeable solid against a permeable fluid-containing porous medium, and
c. a fluid against a permeable fluid-containing porous medium. This is in principle the Zwikker and Kosten problem of sound absorption by porous walls.

a. *The ordinary solid-solid case*

For the solid-solid case equation (65) through (68) reduce to

$$A_{1i} = \frac{1}{2}\left(1 + \frac{l_1' H'}{l_1 H}\right) A_1'$$

and

$$A_{1r} = \frac{1}{2}\left(1 - \frac{l_1' H'}{l_1 H}\right) A_1',$$

as $A_2 = 0$, while

$$l_1 H = \omega\sqrt{\rho H}$$

for pure solids. For this system the well-known expression for the absorption coefficient at the interface is obtained:

$$\alpha = 1 - \left(\frac{l_1 H - l_1' H'}{l_1 H + l_1' H'}\right)^2. \tag{76}$$

b. *An impermeable solid against a fluid-containing permeable porous solid.*

If an elastic wave passes through an interface separating a non-permeable solid and a fluid saturated permeable porous solid a somewhat analogous situation as considered above is met. Let us assume that the first medium is an impermeable solid. Then

$$\beta = 1, \quad H = \frac{1}{c_s} + \frac{4}{3} G_s, \quad L = \infty, \quad K = 0,$$

$$m_1 = 0, \quad m_2 = \infty, \quad l_1 = \omega \sqrt{\frac{\rho}{H}}, \quad l_2 = \infty.$$

So we have

$$(A_{1i} + A_{1r}) + (A_{2i} + A_{2r}) = A_1' + A_2',$$

$$A_{2i} + A_{2r} = 0,$$

$$A_{1i} - A_{1r} = \frac{H' l_1'}{H l_1} A_1',$$

and

$$A_2' = 0.$$

Accordingly again

$$A_{1i} = \frac{1}{2}\left(1 + \frac{l_1' H_1'}{l_1 H}\right) A_1',$$

$$A_{1r} = \frac{1}{2}\left(1 - \frac{l_1' H_1'}{l_1 H}\right) A_1',$$

and the result is analogous with the ordinary solid-solid case, with the exception that now H' represents the total compressibility of the fluid-saturated porous medium. Again

$$\alpha = 1 - \left(\frac{l_1 H - l_1' H'}{l_1 H + l_1' H'}\right)^2. \tag{76}$$

No second wave is generated at an interface of two media of which one is impermeable ($A_2' = B_2' = 0$).

c. *A fluid against a permeable porous fluid saturated material.*

If one of the two media is a fluid, and if this is the first medium, the situation at the boundary is quite different. Now

$$H = K = L = 1/c_l.$$

Furthermore,

$$A_{2i} - B_{2i} = 0 \quad \text{and} \quad A_{2r} - B_{2r} = 0.$$

With

$$A_{1i} - B_{1i} = D_1$$

and

$$A_{1r} - B_{1r} = D_2,$$

one obtains

$$D_1 + D_2 = A_1' + \left(1 - \frac{H'}{K'}\right) A_2',$$

$$H l (D_1 - D_2) = H' l_1' A_1'$$

$$= K' l_1' A_1' + K' \left(1 - \frac{L' H'}{K'^2}\right) l_2' A_2',$$

and the absorption coefficient reads:

$$\alpha = 1 - \left|\frac{D_2}{D_1}\right|^2,$$

with

$$D_1 = \frac{1}{2}\left[\left(1 + \frac{H' l_1'}{H l}\right) - \frac{\left(1 - \frac{H'}{K'}\right)^2 l_1'}{\left(1 - \frac{L' H'}{K'^2}\right) l_2'}\right] A_1'$$

and

$$D_2 = \frac{1}{2}\left[\left(1 - \frac{H' l_1'}{H l}\right) - \frac{\left(1 - \frac{H'}{K'}\right)^2 l_1'}{\left(1 - \frac{L' H'}{K'^2}\right) l_2'}\right] A_1'. \tag{77}$$

In acoustics, the assumption that the porous skeleton is entirely rigid is allowed for many sound-absorbing materials, which means that we may put

$$H' = \infty, \quad K' = 0, \quad L' = \frac{1}{\phi c_l} = \frac{H}{\phi},$$

$$l_1' = 0, \qquad l_2' = (1 - j)\omega \sqrt{\frac{\rho'}{2L'} \frac{\omega_c'}{\omega}}.$$

For this situation the equation for the absorption coefficient reduces to

$$\alpha = 1 - \left| \frac{Hl - L'l_2'}{Hl + L'l_2'} \right|^2,$$

or

$$\alpha = 1 - \left| \frac{\phi l - l_2'}{\phi l + l_2'} \right|^2 \tag{78}$$

(compare with Zwikker (1950)).
As

$$l_2' = -(1 - j)a$$

$$\left(\text{taking } a = \omega \sqrt{\frac{\rho'}{2L'} \frac{\omega_c'}{\omega}}\right)$$

we have

$$\alpha = 1 - \left| \frac{(\phi l - a) + ja}{(\phi l + a) - ja} \right|^2$$

$$= 1 - \frac{(\phi l - a)^2 + a^2}{(\phi l + a)^2 + a^2}.$$

And as $a \gg \phi l$,

$$\alpha \approx 2 \sqrt{\frac{2\omega k \rho_l \phi}{\mu}}. \tag{79}$$

Remembering that

$$V_2' = \sqrt{\frac{2k\omega}{\mu \phi c_l}},$$

we can write for the relationship between sound absorption coefficient and wave velocity in the absorbing material

$$\alpha \approx 2\phi^2 c_l^2 V_2'. \tag{80}$$

DISCUSSION

One of the outcomes of this investigation was a better picture of the significance and the influence of the so-called wave of the second kind on the propagation of stress waves in an elastic, porous, fluid-saturated material. We have demonstrated that such a wave is generated at any interface between dissimilar fluid-saturated porous media and also at any interface between a fluid and a fluid-saturated porous medium. The latter case has already been met in the theory of sound absorption by porous walls in acoustics. But though in the theory of sound-absorbing porous walls the wave of the second kind is the main cause of the sound absorption, its role in seismics will in general be rather small. The reason for this is that if the fluid is a liquid, and the porous material is a sedimentary rock, the mobility of the pore content becomes small.

We have also found the basic relationship between dilatational wave velocity on the one hand and the compressibilities and densities of the components of a fluid-saturated porous medium on the other hand. This relation is a function of frequency. In seismic work the theoretical solution for zero frequency will roughly represent the correct wave velocity.

Some years ago Wyllie et al (1956) suggested an equation for the wave velocity in a fluid-saturated porous material, the so-called "time-average relation," based on the dubious assumption that the porous medium can be replaced by a series of alternating solid and liquid layers, which the wave front passes perpendicular to the interfaces between both phases. Surprisingly this relationship, when applied to sonic-log interpretation, predicted a porosity value which was believed to be close to reality in many sandstone reservoirs. As a result a series of engineering publications followed in which this time-average relation was applied to different situations for which it had to be extrapolated beyond proportion. There is of course nothing against the use of an engineering formula based on an over-simplified model, as long as such a formula is of help in obtaining valuable data. But the frequent use of the time-average relation has surrounded it with an aura of scientific truth. Also, the danger existed that research on this subject should be guided in the wrong direction. For instance, the time-average relation entirely neglects the important role of the bulk deformation properties of the rock material, which are pressure-dependent. The present theory tries to restore the right perspective by clearly showing the proper contribution of each of the elastic properties of rock matrix, rock bulk material and pore fluid to the wave velocity. According to this point of view,

the main subject of research has to be the study of the influence of porosity, grain size distribution, grain cementing material etc. on rock bulk compressibility. These data can be obtained both from static and from dynamic loading tests.

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GEOPHYSICS, VOL. XXVI, NO. 2 (APRIL, 1961), PP. 182–191, 11 FIGS.

QUANTITATIVE INTERPRETATION OF GAMMA-RAY LOGS*

J. H. SCOTT,† P. H. DODD,† R. F. DROULLARD,† P. J. MUDRA†

Abstract: A quantitative method for determining the concentration of gamma-ray emitting elements in layered rocks penetrated by boreholes has been developed by the U. S. Atomic Energy Commission. It is based on the relationship

$$\overline{G}T = k\int_{-\infty}^{+\infty} I dz$$

where $\overline{G}$ is the mean thickness T, k is a constant of proportionality, and I is the intensity of the gamma-ray field along the borehole axis at a distance z from a fixed point of reference on the axis. This relationship has been confirmed theoretically and empirically.

In application, the grade-thickness product of a mineralized zone intersected in the borehole is determined by multiplying the area under the gamma-ray log curve by a constant of proportionality. The mean grade of the zone is determined by dividing the grade-thickness product by the zone thickness. Corrections applied for nonstandard conditions in the borehole reduce the data to equivalence with standard calibration conditions. Because the volume sampled in this logging method is significantly larger than that of core samples, the resulting data are more representative than data from chemically-assayed core.

INTRODUCTION

One of the responsibilities of the Division of Raw Materials of the U. S. Atomic Energy Commission (AEC) is the determination of current reserves of uranium ore in the United States. When the uranium mining industry was in its infancy, chemical assays of drill core samples provided most of the data from which uranium ore reserves were calculated. In recent years core data have been largely replaced by grade and thickness information derived from gamma-ray logs of noncored holes, resulting in lower exploration cost. With the development of improved equipment and interpretive procedures, accurate interpretations of gamma-ray logs are now possible.

Various gamma-ray log interpretive procedures have been described by Broding and Rummerfield (1955), Suppe (1957), and Droullard and Dodd (1958). The present paper describes an interpretive procedure based on the same principles, but incorporating certain improvements over the procedure reported by Droullard and Dodd (1958). Although the method has been applied specifically to uranium deposits, the principles upon which it is based are generally applicable to deposits of other elements which either emit gamma rays or are quantitatively related to gamma-ray emitters.

BASIC PRINCIPLES

The interpretive method is based on the proportionality between the corrected area under the log curve and the product of the mean grade and thickness of the layer of radioactive material. This relationship is expressed by the equation

$$\overline{G}T = k\int_{-\infty}^{+\infty} I dz \qquad (1)$$

where $\overline{G}$ is the mean concentration of a radioactive element by weight, T is the thickness of the layer containing the radioactive element, k is a constant of proportionality, I is the intensity of the gamma-ray field at a point on the borehole axis, and z is the distance between this point and a fixed point of reference on the axis.

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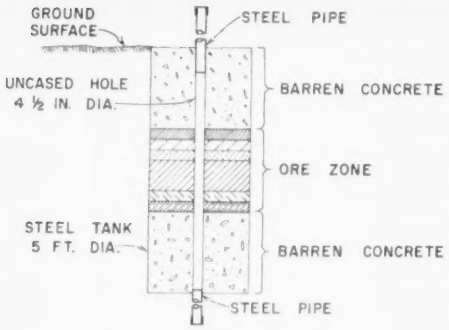

FIG. 1. Calibration model.

For practical application the equation has been expressed as

$$\overline{G}_\gamma T = kA \qquad (2)$$

where $\overline{G}_\gamma$ is the average radiometric grade of uranium ore, expressed in percent equivalent U_3O_8 by weight, T is the thickness of the ore zone in feet, k is a constant of proportionality determined by instrument calibration, and A is the corrected area under the gamma-ray log curve.

The validity of the method has been demonstrated empirically by using full scale models which simulate boreholes drilled through uranium-bearing rock layers. Figure 1 shows a cross-section of one of several models constructed by the AEC for testing and calibration purposes. Each model contains cemented layers of barren sand and crushed uranium ore. The mean radiometric equivalent grade and the thickness of each layer is known accurately. Gamma-ray logs have been obtained in each model and the area under the anomalous part of each log curve has been determined and plotted against the known grade-thickness product of the corresponding ore zone as shown in Figure 2. In this figure each point falls within 3 percent of a straight line drawn through an average value and the origin. This substantiates the proportionality between the area-under-the-curve and the grade-thickness product.

Further corroboration has been obtained by using gamma-ray logging data from natural uranium deposits, an example of which is given in Figure 3. In this figure the areas under the log curves are plotted against grade-thickness products determined from corresponding core samples. The scatter of the points can be attributed largely to

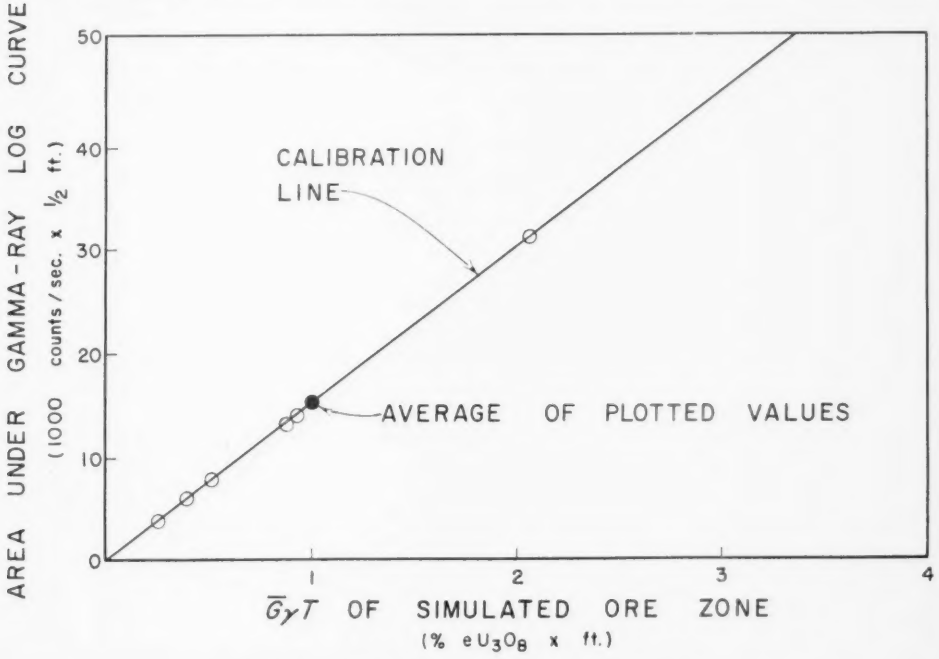

FIG. 2. Gamma-ray logging data from calibration models.

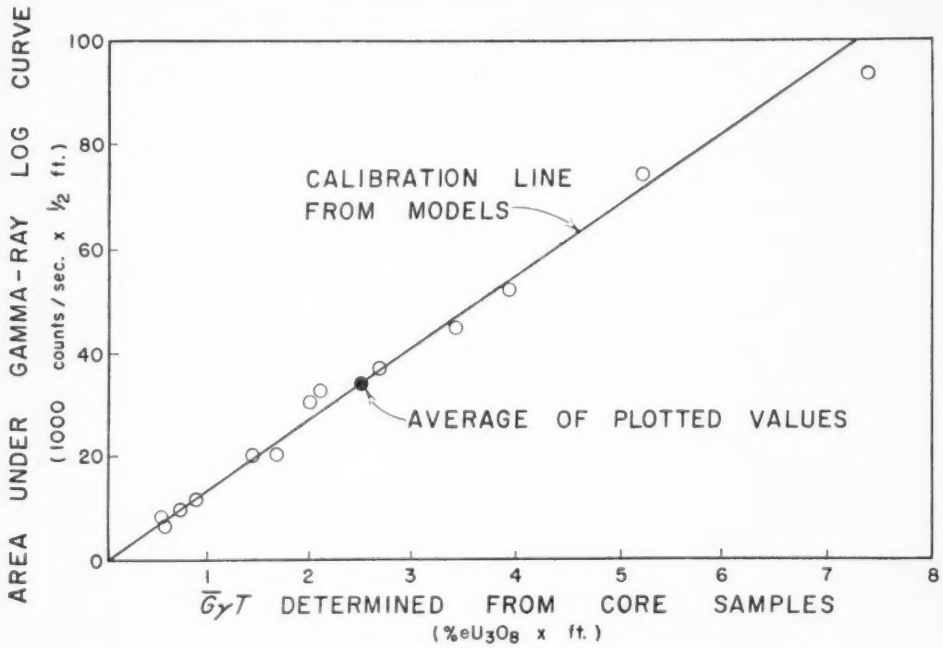

FIG. 3. Gamma-ray logging data from a uranium deposit compared with calibration from models.

the inhomogeneity of natural uranium ore. In comparing the core data to the gamma-ray log data, it should be remembered that physically different volumes of rock are sampled in each case. Considering the inhomogeneity of the material, a perfect correlation would not be expected. It is significant, however, that a rather good correlation exists, and that the average area under the curve, when plotted against the average $\overline{G}_\gamma T$, falls on the calibration line derived using the models. An important advantage of gamma-ray logging over core sample analysis is that the volume of material "sampled" by the gamma-ray detector is larger, and hence more nearly representative, than the core sample.

The equation $\overline{G}_\gamma T = kA$ can be justified theoretically as follows. The intensity of a gamma-ray field at a point of measurement separated from a point source of gamma rays is given by

$$I_p = \frac{I_o e^{-\mu x} B(\mu x)}{4\pi x^2} \tag{3}$$

where I_p is the intensity of the gamma-ray field at a point of measurement, I_o is the initial gamma-ray intensity at the point source, μ is the linear absorption coefficient of the environmental medium, and x is the distance between the point source and the point of measurement, of the gamma rays. In equation (3) the term $e^{-\mu x}$ accounts for the absorption of gamma rays by the environmental medium. The function $B(\mu x)$ is the so-called buildup factor, which accounts for the buildup of gamma-ray intensity due to scattering. The term $4\pi x^2$ is an expression of the inverse square law.

Since gamma rays emanating from a differential volume can be assumed to duplicate the effect of gamma rays emanating from a point source, the point source may be replaced with a differential volume, dV. If the material of which dV is composed is uranium ore, the initial intensity of gamma rays, I_o, is proportional to the weight, dW, of U_3O_8 present in the differential volume; that is,

$$I_o = c\,dW \tag{4}$$

where c is a constant of proportionality.

Since the radiometric equivalent grade of U_3O_8, G_γ, is to be determined as a percent concentration by weight,

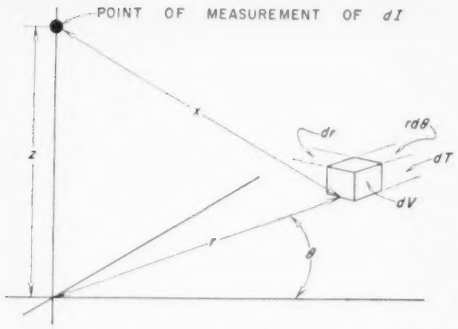

FIG. 4. Differential volume dV in a cylindrical coordinate system.

$$G_\gamma = 100\frac{dW}{\rho dV} \tag{5}$$

where ρ is the density of the ore. Upon solving equation (5) for dW, and substituting the result for dW in equation (4), we obtain

$$I_o = \frac{c\rho dV G_\gamma}{100}. \tag{6}$$

A differential equation for the intensity resulting from the differential volume can now be developed from equations (3) and (6):

$$dI = \frac{c\rho G_\gamma}{100}\frac{e^{-\mu x}B(\mu x)dV}{4\pi x^2}. \tag{7}$$

If the differential volume and a point of measurement are placed in a cylindrical coordinate system, as shown in Figure 4, the dimensions: $rd\theta$, dr, and dT can be assigned to dV.

Thus $dV = rdrd\theta dT$, and by substitution equation (7) becomes

$$dI = \frac{c\rho G_\gamma}{100}\frac{e^{-\mu x}B(\mu x)}{4\pi x^2} rdrd\theta dT. \tag{8}$$

From the geometrical relations shown in Figure 4, $x^2 = r^2 + z^2$. Therefore,

$$dI = \frac{c\rho G_\gamma}{100}\frac{e^{-\mu\sqrt{r^2+z^2}}B(\mu\sqrt{r^2+z^2})}{4\pi(r^2+z^2)} rdrd\theta dT. \tag{9}$$

A slab of uranium ore of dT thickness, having a circular hole concentric with the vertical axis, is shown in Figure 5. At a point on the vertical axis the gamma-ray intensity I_s resulting from the slab can be determined by integrating the element of

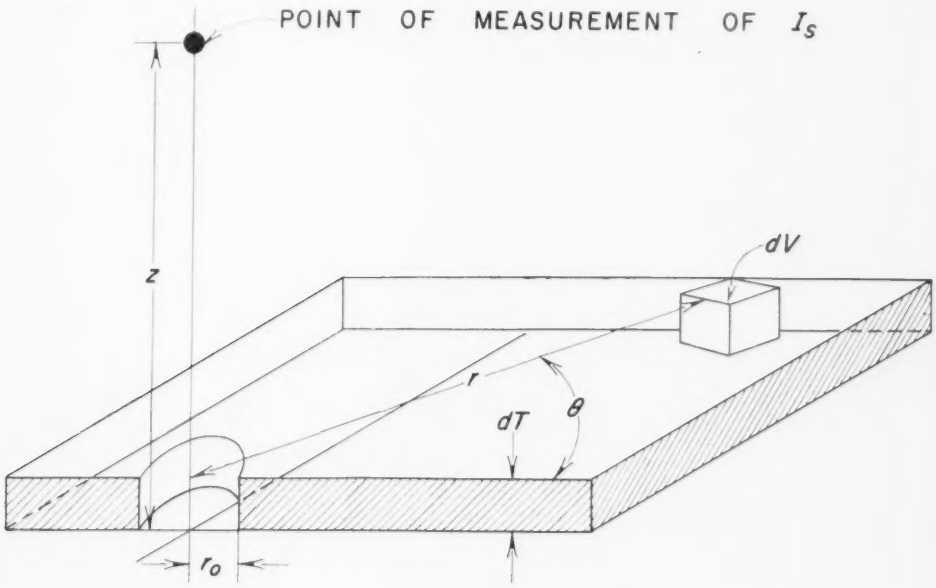

FIG. 5. Gamma-ray intensity from slab source, thickness = dT.

volume around the axis from $\theta=0$ to $\theta=2\pi$, and outward from $r=r_0$ (on the edge of the hole) to $r=\infty$. Thus,

$$I_s = \frac{c\rho G_\gamma dT}{100}\int_0^{2\pi}\int_{r_o}^{\infty} \frac{e^{-\mu\sqrt{r^2+z^2}}B(\mu\sqrt{r^2+z^2})}{4\pi(r^2+z^2)}\, r dr d\theta. \tag{10}$$

Equation (10) can be evaluated numerically. For the purposes of this development it is only necessary to state that after integration the integrand of equation (10) becomes a function of r_o, z, and μ, and

$$I_s = \frac{c\rho G_\gamma dT}{100} f(r_0, z, \mu). \tag{11}$$

If calculations of I_s are made at every point along the vertical axis, and I_s is plotted versus z, the result will be a curve which is analogous to a gamma-ray log anomaly resulting from a slab of uranium ore of thickness dT, as shown in Figure 6. The area under this curve, A_s, is given by

$$A_s = \int_{-\infty}^{+\infty} I_s\, dz \tag{12}$$

and by substituting the value of I_s given in equation (11),

$$A_s = \frac{c\rho G_\gamma dT}{100}\int_{-\infty}^{+\infty} f(r_o, z, \mu) dz \tag{13}$$

Upon integration the integrand of equation (13) reduces to a function $g(r_0, \mu)$ so that for simplicity equation (13) may be written

$$A_s \propto G_\gamma dT \rho g(r_o, \mu). \tag{14}$$

Equation (14) indicates that the area under this simple curve is proportional to the radiometric equivalent grade of the uranium ore times its thickness, dT, as long as $\rho g(r_o, \mu)$ remains unchanged. Although in practical application the numerical value of $\rho g(r_o, \mu)$ may change, proportionality between A_s and $G_\gamma dT$ can be re-established by applying appropriate corrections for the variable borehole conditions which cause the change. These corrections will be discussed later. It should be noted that the preceding equations represent an environment consisting of only one medium. For a more perfect analogy, equations could be developed which would take into account the absorption and buildup of gamma rays passing through several media (e.g., rock, borehole fluid, and metallic probe housing). However, such equations would differ from those presented only to the extent that the absorption and buildup terms would be more complex. The general form of the equations would not change, and the proportional relationship between A_s and $G_\gamma dT$ would exist as long as the required corrections were applied for variable borehole conditions.

A uranium ore zone in stratified rock can be considered a layered series of dT-thick slabs. If vertical homogeneity does not exist, each slab is characterized by a discrete grade. If separate curves of I_s versus z are plotted for each slab in the series, and these curves are placed in their natural juxtaposition, a total intensity curve can be obtained by graphically summing all of the overlapping individual curves, as shown diagramatically in Figure 7. The area A under this total intensity curve is given by

$$A \propto G_{\gamma 1}dT + G_{\gamma 2}dT + G_{\gamma 3}dT \tag{15}$$

or, more generally,

$$A \propto \overline{G}_\gamma T \tag{16}$$

where $G_{\gamma 1}$, $G_{\gamma 2}$ and $G_{\gamma 3}$ are the discrete grades of

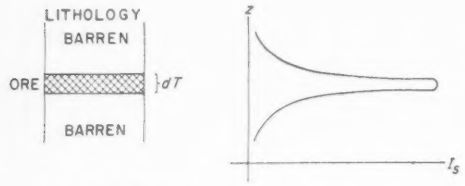

FIG. 6. Gamma-ray intensity curve from slab source, thickness = dT.

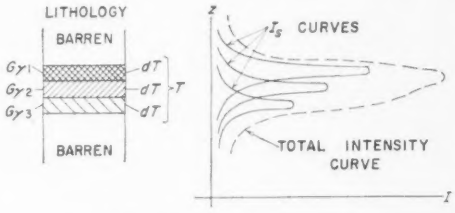

FIG. 7. Gamma-ray intensity curve from slab source, thickness = T.

the individual slabs, $\overline{G}_\gamma$ is the mean radiometric equivalent grade of all individual slabs, dT is the thickness of each slab, and T is the combined thickness of all slabs. Thus, $\overline{G}_\gamma T = kA$, as previously stated.

CORRECTIONS

The validity of the equation $\overline{G}_\gamma T = kA$ depends upon the proper application of corrections for instrument nonlinearity and for variations of physical conditions existing in the vicinity of the borehole. For the instruments used by the AEC, the only significant nonlinearity results from the resolving-time loss inherent in all electronic counting equipment. The true counting rate, corrected for resolving-time loss, is given by the well-known formula

$$N = \frac{n}{1 - nt}, \tag{17}$$

where N is the corrected counting rate, n is the observed counting rate, and t is the resolving time of the instrument.

In order to avoid the monotony and human error which can result from repeated solution of this formula, we have developed transparent overlay graphs which are placed over gamma-ray logs to be interpreted. One such overlay graph is shown in Figure 8. These overlays are designed so that corrected counting rates can be read from the logs directly, using the nonlinear scale of the overlay.

Corrections are made for variations of physical conditions existing in vicinity of the borehole. These corrections reduce logging data to equivalence with standard conditions in full-scale calibration models previously described. No correction is made for dry bulk density, as mathematical approximations and empirical tests indicate any effects are less than experimental errors. Physical conditions subject to significant variation and the corresponding AEC standard conditions are given in Table I.

The numerical values of correction factors for the first four conditions can be determined semi-empirically by using full scale models. These correction factors depend, in part, on the spectral

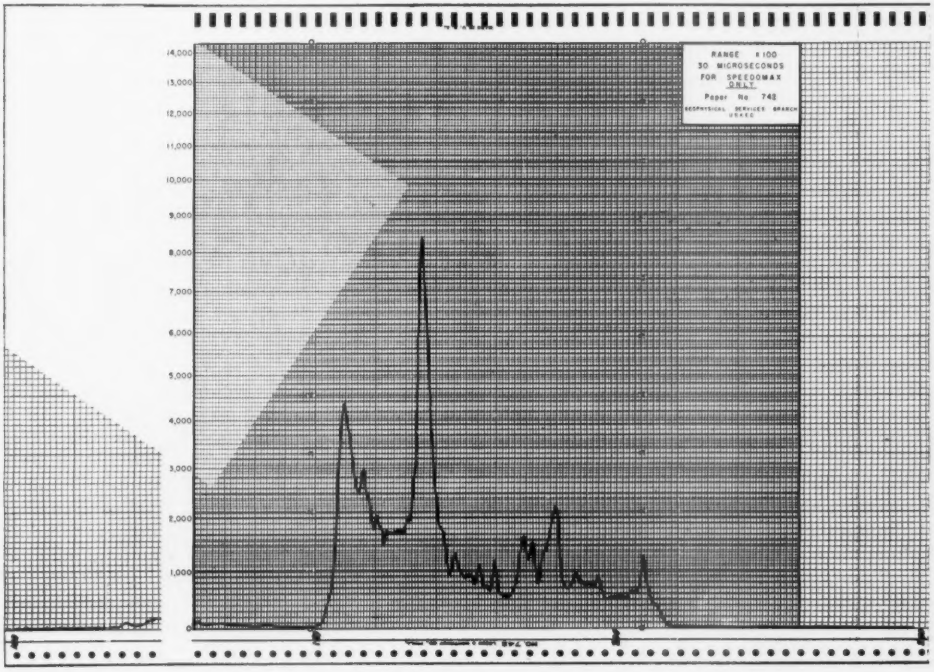

FIG. 8. Resolving time correction overlay.

TABLE I. BOREHOLE CONDITIONS FOR WHICH CORRECTIONS ARE REQUIRED

Variable Condition	AEC Standard Condition
1. Borehole diameter	4½ inches
2. Medium filling the borehole	Air
3. Borehole casing	None
4. Water content of ore	12 percent (by weight)
5. Disequilibrium	$\overline{G}_t/\overline{G}_\gamma = 1$

response of logging equipment. Therefore, it is necessary to make individual correction factor determinations for each type of equipment.

The correction factor for the fifth variable condition, disequilibrium, is represented by the ratio of the mean true grade $\overline{G}_t$ to the mean radiometric equivalent grade $\overline{G}_\gamma$ of an ore deposit. This ratio can be estimated by making a statistical analysis of the results of laboratory assays of samples obtained from the area. Each sample is assayed for percent U_3O_8 (weight) by chemical and by radiometric techniques. When the laboratory radiometric assay is made, only gamma radiation is measured. We have termed this type of assay the "gamma-only" assay. Gamma-only assays, rather than beta or beta-gamma assays, are required because the laboratory measurement must be analogous to the logging measurement, and the logging probe detects only gamma rays.

In making gamma-only assays, the possibility of radon escape must be considered. Bi^{214}, the most significant gamma-ray-emitting isotope in the uranium series, is controlled quantitatively by the amount of radon present in a sample. If radon escapes during sample preparation, the quantity of Bi^{214} in the sample becomes abnormally low, causing the value of the gamma-only assay to be too low also. If this incorrect value is used to determine the disequilibrium correction factor, the factor will be too high. This error is avoided by sealing the prepared sample in a gas-tight container and making two "apparent" assays, the first at least four hours after sealing and the second a few days later. By entering these two "apparent" assay values and the lapsed-time interval into a formula based on the exponential reaccumulation of radon, the true value is calculated (Scott and Dodd, 1960).

PRACTICAL APPLICATION

The discussion thus far has concerned the principles upon which the interpretive technique is based, and a specific description of the corrections which are required. A simple step-by-step procedure has been developed for routine application of the technique. First the thickness of the ore zone is determined and entered on a work sheet. It has been demonstrated theoretically and empirically that for ore zones two feet or more in thickness which have relatively sharp boundaries, the ore boundary is quite accurately represented by the half-amplitude point on the flank of the anomaly. Errors in thickness estimation caused by gradational boundaries, or by thicknesses less than two feet, have proven insignificant in ore reserve calculations. Therefore, thickness is determined by measuring the amplitudes of the peaks nearest the top and bottom of the anomaly, and calculating the footage interval between the half-amplitude points on the log curve as shown in Figure 9.

Next, the area under the curve is determined. Counting rate values are read off the log curve using the transparent overlays which correct for resolving-time losses. These values are entered on the work sheet. The first counting rate value is read at the previously-determined upper half-amplitude point. This value is called the first end value, E_1, as shown on Figure 10. Successive intermediate values designated by I_1, I_2 etc., are read at positions equivalent to half-foot depth intervals in the hole. The last intermediate value to be read is just above the lower boundary of the ore zone. The second end value, E_2, is read one interval below the last value, and just below the lower boundary of the ore.

The total area under the anomalous part of the curve can be subdivided into two tail areas and a central area as shown in Figure 11. Each tail area extends to a point halfway between an E point and the adjacent I point. The value of the sum of the two tail areas is approximated by adding together the counting rate values at E_1 and E_2 and then multiplying by a "tail factor." A tail factor of 1.38 is used for AEC logging equipment when counting rate values are read at half-foot intervals. As long as both end values, E_1 and E_2, are read at or below the half-amplitude levels of the adjacent peaks on the logs, the error of this approximation is usually less than 2 percent of the total area under the curve.

The value of the central area between the two tail areas is determined by summing the intermediate values represented by I_1, I_2, I_3 etc. This

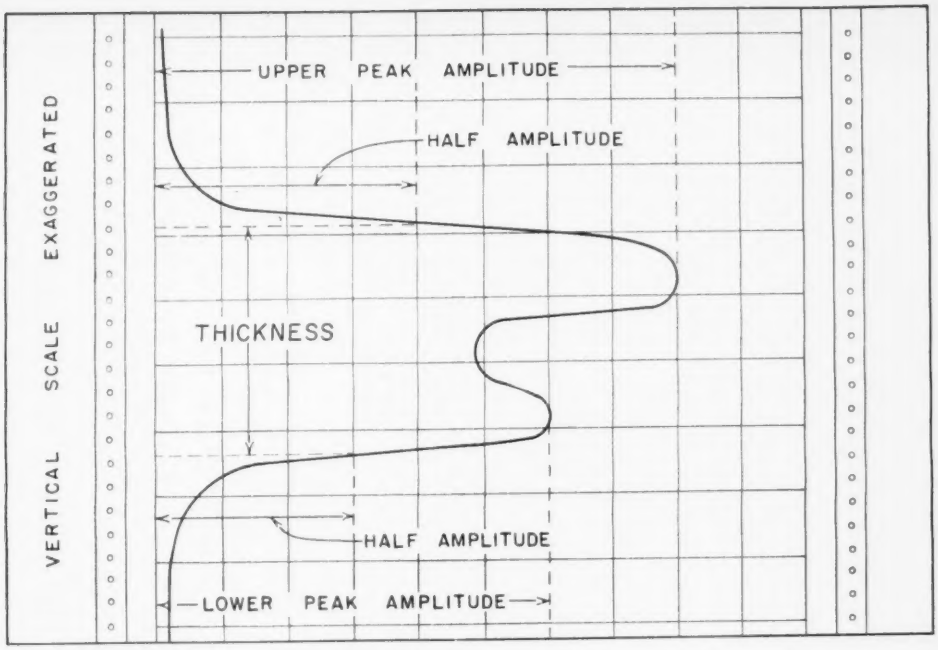

FIG. 9. Thickness determination.

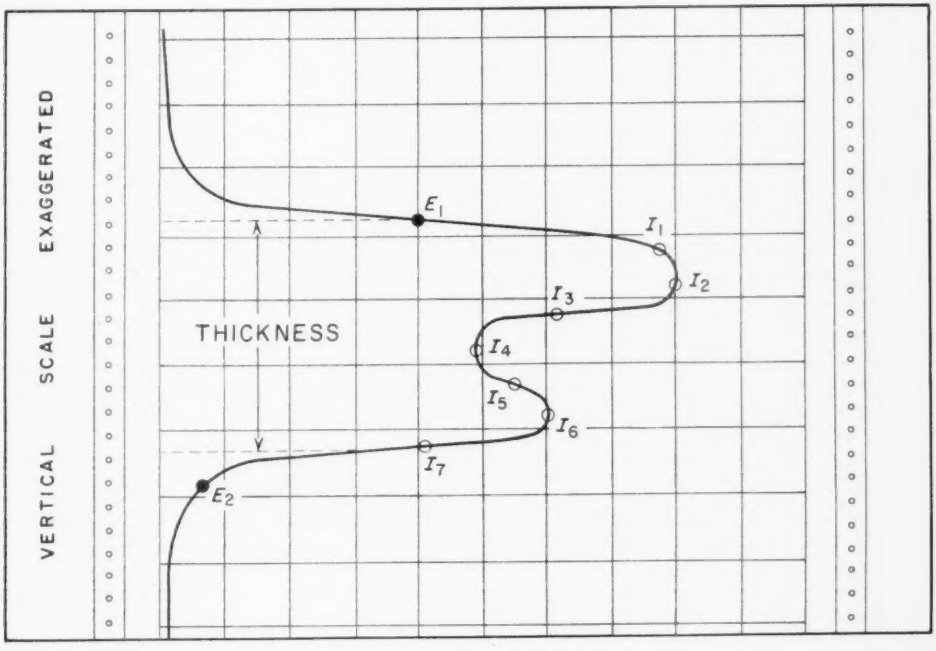

FIG. 10. Numerical integration points.

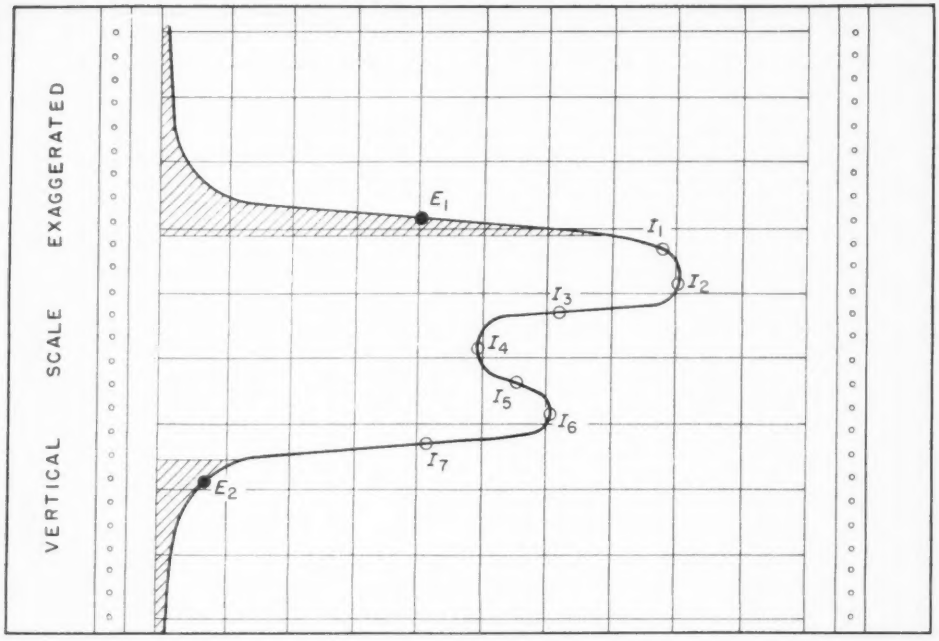

FIG. 11. Determination of tail areas and central area.

is a trapezoidal-type numerical integration which results in an error which is usually less than 3 percent. The value of the total area under the anomalous part of the curve is then determined by adding the value of the combined tail areas to the value of the central area.

The value of the total area is multiplied by correction factors for the first four borehole conditions listed in Table I. The resulting corrected value is then multiplied by the calibration factor, k, to obtain $\overline{G}_\gamma T$. $\overline{G}_\gamma T$ is then multiplied by the disequilibrium correction factor to obtain $\overline{G}_t T$, the grade-thickness product of the ore zone corrected for average disequilibrium. $\overline{G}_t T$ is used for calculating ore reserves. Finally, the corrected mean grade $\overline{G}_t$ is determined by dividing $\overline{G}_t T$ by the ore zone thickness T. $\overline{G}_t$ is used for the economic evaluation of ore bodies.

This completes the step-by-step procedure used by the AEC to interpret gamma-ray logs.

SUMMARY

A basic equation $\overline{G}_\gamma T = kA$, has been established which relates the mean radiometric equivalent grade of uranium ore multiplied by the thickness of the layer in which it occurs, to the integrated intensity of the gamma-ray field measured along the axis of a borehole which penetrates the layer. The validity of the equation has been confirmed empirically and theoretically. In practice, the calibration factor, k, is determined for a logging unit by using full scale models. The area under a gamma-ray log anomaly curve is obtained by numerical integration. Corrections are applied for instrument nonlinearity and for nonstandard borehole conditions to obtain the corrected area, A. The grade-thickness product $\overline{G}_\gamma T$, calculated using the basic equation, is corrected for average local disequilibrium. The thickness, T, of an ore layer is determined by measuring the distance between the half-amplitude points on the flanks of the log anomaly curve. Finally, the mean grade corrected for disequilibrium is determined by dividing the corrected grade-thickness product by the thickness.

ACKNOWLEDGEMENTS

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initial work in developing the theoretical proof, and for his constructive review of this paper.

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GEOPHYSICS, VOL. XXVI, NO. 2 (APRIL, 1961), PP. 192-204, 11 FIGS.

PROPAGATION EFFECTS IN INDUCTION LOGGING*

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Abstract: Induction logging utilizes the component of induced receiver coil voltage that is in phase with transmitter coil current as a measure of the conductivity of material surrounding the coils. This paper considers the problem of the field of a vertical magnetic dipole in a horizontally stratified, isotropic conductive formation and shows the receiver coil voltage can be considered as composed of responses due to electromagnetic waves in the formation. These waves which experience attenuation and phase shift as they propagate in the formation are reflected at each interface encountered, and a component of receiver coil voltage is induced for each passage of a wave. The relation of the receiver coil voltage components to the geometric factor of previous analysis is discussed. Universal curves that are useful in determining the response due to unreflected primary and reflected secondary waves are presented Example induction log system responses based on the analysis of the present paper are presented.

NOMENCLATURE

Rationalized MKS units are used unless otherwise specified.

$\boldsymbol{H}$ = Magnetic field intensity
$\boldsymbol{E}$ = Electric field intensity
σ = Electric conductivity
σ_A = Apparent conductivity
μ = Magnetic permeability
$\omega = 2\pi f$ = Radian frequency
$\boldsymbol{\Pi}$ = Hertz vector potential
$\boldsymbol{A}$ = Vector magnetic potential
a = Coil radius
$A = N\pi a^2$ = Effective coil area
N = Number of coil turns
r, z, ϕ = Cylindrical coordinate variables
R, θ, ϕ = Spherical coordinate variables
M = Magnetic dipole moment
$\gamma = \{j\omega\mu\sigma\}^{1/2}$ = Propagation constant
V = Electric potential difference
L = Coil separation
$J_0(\lambda r)$ = Bessel function, first kind, zero order
$F(\lambda)$ = Weighting functions of integral transforms
λ, x = Variable of integration
$\Lambda = \{\lambda^2+\gamma^2\}^{1/2}$
h, k, l = See Figures 2 or 7
$K, \overline{K}$ = Induction coil-pair constants
Δ, δ = Attentuation or phase shift
$\gamma L = \Delta + j\Delta$
G_0 = Relative response to primary excitation
G_n, g_n = Relative response to wave having experienced n reflections
$g(r, z)$ = Geometric factor for infinitesimal toroid
$G(z)$ = Geometric factor for thin layer

Subscripts P or S refer to primary excitation or secondary waves, respectively. Subscripts T, R refer to transmitter or receiver coils. Numerical subscripts on material properties such as σ and field quantities refer to the medium involved. Numerical subscripts on l, Δ, or V refer to the number of reflections experienced by the component in question.

INTRODUCTION

Induction logging is an electromagnetic means of determining the electrical conductivity of strata of earthen formation traversed by a borehole. Discussion of induction logging has centered for many years about the geometric factor concept introduced by Doll. This geometric factor has proved to be valuable since it relates the recorded signal to the conductivity of the formation at positions relative to the transmitter and receiver coils; however, the concept is based on an assumption that cannot be justified if conductive material of the order of one ohm-meter is present

* Manuscript received by the Editor May 23, 1960.

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and if a frequency as high as 20 kc is used with a coil spacing of one meter.

Dumanoir, Tixier, and Martin as well as Tixier, Alger, and Tanguy have published curves of induction log coil systems with "skin-effect" considered. Neither group presents details of the manner in which this effect is taken into account and it is the purpose of this paper to present an analysis in which this effect is considered.

This paper presents a new analysis of the induction log. The new approach considers the receiver coil response as composed of voltages induced by electromagnetic waves propagating through the formation. These waves are generated as primary waves by the transmitter coils and they experience reflection (and transmission) when boundaries separating media are encountered. A component of receiver voltage is induced for each passage of a wave.

The concept presented in this paper is the result of an analysis which follows classical methods of Sommerfeld that have been applied more recently by Sunde, Wait, and others. The approach is a Hankel Transform approach. Evaluation of integrals required to determine the response due to each wave has been accomplished, and curves are presented for these integrals. Example curves of response of 2-coil and 4-coil sondes have been included and the importance of the propagation effect is illustrated by comparison with results of the geometric factor analysis.

This analysis with propagation effects considered is of prime importance in (1) designing coil systems for optimum response and (2) preparing performance charts of an induction log coil system.

THE INDUCTION LOG

A two-coil induction logging system for measuring the electrical conductivity of strata traversed by a borehole is shown schematically in Figure 1. The operation of the system is usually described as follows. A regulated alternating current in the transmitter coil induces current flow in the earthen formation surrounding the borehole. This eddy current is approximately proportional to conductivity and is approximately in phase-quadrature with the transmitter current. The earth currents in turn induce a voltage in the receiver coil that is in phase-quadrature with the earth currents and, hence, in phase with the transmitter current. The mutual coupling between transmitter and receiver coils produces a component of receiver coil voltage independent of conductivity and in phase-quadrature with the transmitter current. The measurement of conductivity is accomplished by phase discrimination in the receiver. Practical induction logging systems utilize multiple coil combinations designed to focus the response to strata immediately adjacent to the sonde.

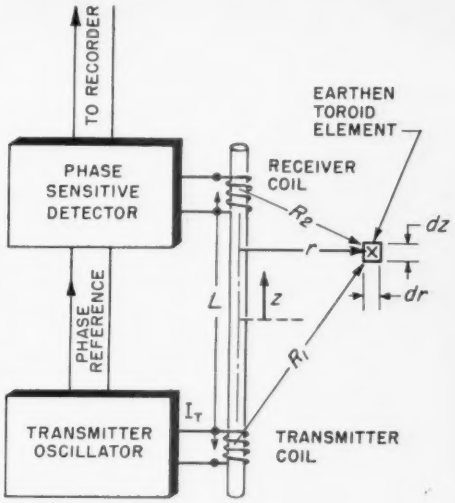

FIG. 1. Induction log schematic.

Although the foregoing discussion serves to describe the operation of the induction log, the following limitation exists. When a frequency of 20 kc is used in highly conductive material of the order of 1 ohm-meter, then coil spacings of 40 inches as used in practice become appreciable to a wave length. The propagation effects of attenuation and phase shift as functions of position then assume importance and should be considered in an analysis of the system response. The object of the study that follows is to determine induction log response with full consideration being given to the propagation or "skin" effect. Three cases are studied; these are the cases of the sonde located (a) in a homogeneous medium, (b) near an interface, and (c) in a bed.

Presentation of the geometric factor concepts is given later in a discussion of results where comparison with results of this paper is made.

ANALYSIS OF THE INDUCTION LOG

Vector Field Equations

For sinusoidally varying fields with time variation taken as $\epsilon^{j\omega t}$, Maxwell's Equations can be expressed as equations (1) and (2) below. The field quantities are phasors in rationalized MKS units. In the conductive earth $\omega\epsilon$ is neglected in comparison to conductivity σ.

$$\nabla \times \boldsymbol{H} = \boldsymbol{J} = \sigma \boldsymbol{E} \tag{1}$$

$$\nabla \times \boldsymbol{E} = -j\omega \boldsymbol{B} = -j\omega\mu \boldsymbol{H}. \tag{2}$$

It is mathematically convenient to derive the field quantities from the Hertz vector field $\boldsymbol{\Pi}$ or from the vector magnetic field $\boldsymbol{A}$ where

$$\boldsymbol{H} = \nabla \times \nabla \times \boldsymbol{\Pi} = \nabla \times \boldsymbol{A}/\mu \tag{3}$$

$$\boldsymbol{E} = -j\omega\mu \nabla \times \boldsymbol{\Pi} = -j\omega \boldsymbol{A}. \tag{4}$$

The components of the Hertz vector field satisfy the wave equation

$$\nabla^2 \boldsymbol{\Pi} = \gamma^2 \boldsymbol{\Pi} = j\omega\mu\sigma \boldsymbol{\Pi}. \tag{5}$$

We seek solutions of equation (5) that exhibit proper behavior at the exciting transmitter coils, at infinite radii, and at boundaries separating differing media. The receiver coil voltage can be determined from these solutions through use of equations (3) or (4).

Sonde in a Homogeneous Medium

Let the transmitter coil with dipole moment $M = \pi a_T^2 N_T I_T = A_T I_T$ be aligned with the z-axis and located at the origin in a homogeneous medium. The Hertz vector field is given by

$$\boldsymbol{\Pi} = \boldsymbol{k}\Pi = \boldsymbol{k} M \epsilon^{-\gamma R}/4\pi R. \tag{6}$$

The electric field is derived from $\boldsymbol{\Pi}$ as

$$\begin{aligned} E_\phi &= -j\omega\mu \frac{\partial \Pi}{\partial r} \\ &= j\omega\mu M \sin\theta (1 + \gamma R)\epsilon^{-\gamma R}/4\pi R^2. \end{aligned} \tag{7}$$

Let the receiver coil be located at $z = L$ and aligned with the z-axis. The voltage induced in the receiver coil can be obtained by evaluating the line integral around the coil.

$$V = \int_{\text{coil}} \boldsymbol{E} \cdot d\boldsymbol{R} = 2\pi N_R a_R E_\phi. \tag{8}$$

For the receiver coil we take $L \gg a_R$ so in the above integral $R \doteq L$, $r = a_R$, $\sin\theta \doteq a_R/L$. There results

$$V = j \frac{\omega\mu A_T A_R I_T}{2\pi} \frac{(1 + \gamma L)\epsilon^{-\gamma L}}{L^3}. \tag{9}$$

A power series expansion can be developed for $(1+\gamma L)\epsilon^{-\gamma L}$ which when substituted gives

$$\begin{aligned} V = j \frac{\omega\mu A_T A_R I_T}{2\pi L^3} \{ & 1 - (j\omega\mu\sigma)L^2/2 \\ & + (j\omega\mu\sigma)^{3/2} L^3/3 - (\omega\mu\sigma)^2 L^4/8 \\ & + (j\omega\mu\sigma)^{5/2} L^5/30 + \quad \}. \end{aligned} \tag{10}$$

The first term of the above equation,

$$(j\omega\mu A_T A_R I_T)/2\pi L^3,$$

is the mutual inductance voltage. The second term of the series is proportional to conductivity σ and is in phase with transmitter current I_T. This second component, $\sigma(\omega^2\mu^2 A_T A_R I_T)/4\pi L$, is the solution given by Doll's analysis. The remainder of the terms of the series give the correction that should be taken into account for "skin-effect" or propagation-effect.

In induction logging instrumentation the quadrature or mutual inductance term is nulled and the in-phase component of the receiver voltage is determined by phase sensitive detection. This in-phase component of voltage divided by the true conductivity is given in terms of the dimensionless number $\Delta = L\{\omega\mu\sigma/2\}^{1/2}$ as

$$\begin{aligned} \sigma_A/\sigma = G_0 = 1 - \frac{2\Delta}{3} + \frac{2}{15}\Delta^3 \\ - \frac{1}{18}\Delta^4 + \end{aligned} \tag{11}$$

and is plotted as Figure 3.

Sonde near a Plane Interface Separating Differing Media

Consider the important case of a coil system approaching the interface separating two semi-infinite media of differing conductivity with nomenclature as defined on Figure 2(b). The solution can be obtained through utilization of the integral transform method of Sommerfeld (pp. 236–278). It can be shown that solutions of the

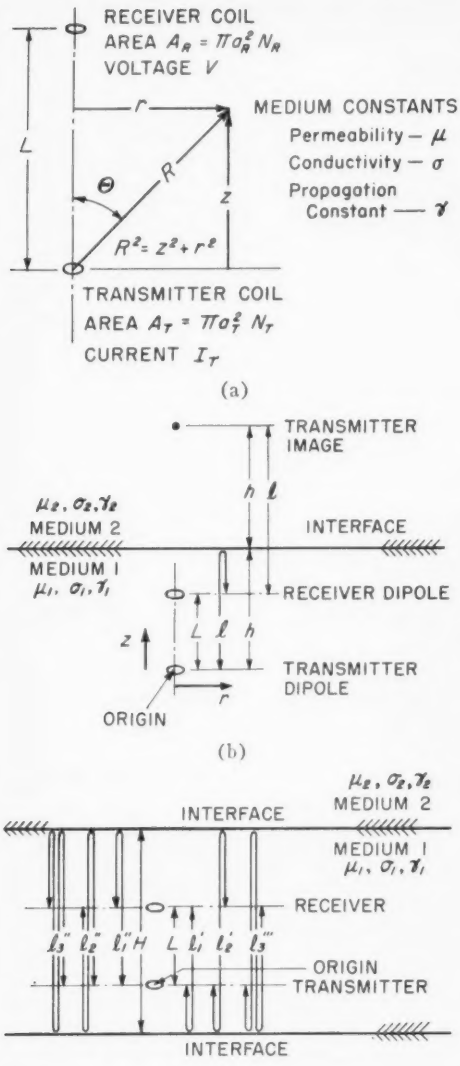

FIG. 2. Illustration of three problems considered with definition of symbols used in analysis.

wave equation, equation (5), can be expressed as Hankel Transforms as

$$\Pi = \int_0^\infty F(\lambda) J_0(\lambda r) \epsilon^{-\Lambda z} d\lambda \tag{12}$$

$$\Lambda^2 = \lambda^2 + \gamma^2, \tag{13}$$

where $J_0(\lambda r)$ is the First Kind, Zero Order Bessel Function. In region 1 the solution is taken to be the primary excitation function,

$$\Pi_{1P} = M\epsilon^{-\gamma R}/4\pi R,$$

plus a perturbation due to the discontinuity. An integral transform of the primary excitation is given by Erdelyi (equation (24), page 9) with $F(\lambda) = \lambda/\Lambda$. Thus, where $\mathbf{\Pi}_1 = \mathbf{\Pi}_{1P} + \mathbf{\Pi}_{1S}$

$$\Pi_1 = \frac{M}{4\pi} \int_0^\infty J_0(\lambda r) \cdot \left\{ \frac{\lambda}{\Lambda_1} \epsilon^{-\Lambda_1 |z|} + F_1(\lambda) \epsilon^{\Lambda_1 z} \right\} d\lambda \tag{14}$$

$$\Lambda_1^2 = \lambda^2 + \gamma_1^2. \tag{15}$$

In region 2, $\Lambda_2^2 = \lambda^2 + \gamma_2^2$

$$\Pi_2 = \frac{M}{4\pi} \int_0^\infty F_2(\lambda) J_0(\lambda r) \epsilon^{-\Lambda_2 z} d\lambda. \tag{16}$$

Conditions that must be satisfied at the interface are used to solve for the weight factors $F_1(\lambda)$ and $F_2(\lambda)$. Boundary conditions relating tangential and normal components of the field quantities at $z = h$ are $E_{\phi 1} = E_{\phi 2}$, $H_{r1} = H_{r2}$ and $\mu H_{z1} = \mu H_{z2}$. Since only a z-component of $\mathbf{\Pi}$ is required here, equations (3) and (4) lead to conditions at $z = h$ that must be satisfied for Π; namely $\Pi_1(r, h) = \Pi_2(r, h)$ and

$$\frac{\partial \Pi_1}{\partial z} = \frac{\partial \Pi_2}{\partial z}.$$

The boundary conditions and the property of Fourier-Bessel integrals given on page 183 of Smythe permit solution for $F_1(\lambda)$ and $F_2(\lambda)$. On application of these relations and solution for $F_1(\lambda)$ and $F_2(\lambda)$, there results

$$F_1(\lambda) = \frac{\lambda}{\Lambda_1} \left(\frac{\Lambda_1 - \Lambda_2}{\Lambda_1 + \Lambda_2} \right) \epsilon^{-2\Lambda_1 h} \tag{17}$$

$$F_2(\lambda) = \left(\frac{2\lambda}{\Lambda_1 + \Lambda_2} \right) e^{+(\Lambda_2 - \Lambda_1)h}. \tag{18}$$

The voltage induced in the receiver coil can be determined as the product of $(-j\omega)$, coil area, and axial component of magnetic flux density evaluated at the receiver coil. An alternative

method is to evaluate $\int \boldsymbol{E}\cdot d\boldsymbol{R}$ over the receiver coil whence

$$V = 2\pi a_R N_R E_\phi \tag{19}$$

$$V = (2\pi a_R N_R)(-j\omega\mu)\cdot\left[\frac{\partial \Pi}{\partial r}\right]_{r=a_R}^{z=L}. \tag{20}$$

It is convenient to divide V into two components, V_P and V_S resulting from the primary and secondary fields, respectively. V_P has been evaluated previously as equations (9) and (10) with its real component given as equation (11). Although the wave number λ runs the range from zero to infinity, the integral converges rapidly so that for small receiver coil radius a_R we can consider $\lambda a_R \ll 1$. Equations (14), (17), and (20) give V_S. With the approximation for

$$\lambda a_R \ll 1,$$

$$\frac{\partial J_0(\lambda r)}{\partial r} = -\lambda J_1(\lambda r) \doteq -\lambda^2 r/2,$$

and equations (14), (17) and (20), there results

$$V_S = \frac{K}{2}\int_0^\infty \frac{\lambda^3}{\Lambda_1}\left(\frac{\Lambda_1-\Lambda_2}{\Lambda_1+\Lambda_2}\right)\epsilon^{-\Lambda_1 l}d\lambda \tag{21}$$

where $l=(2h-L)$ and K is the constant

$$K = j\omega\mu A_R A_T I_T/2\pi. \tag{22}$$

We observe l to be the distance traveled from transmitter to interface to receiver and $(\Lambda_1-\Lambda_2)/(\Lambda_1+\Lambda_2)$ as the reflection coefficient at the interface.

The induction log receiver coil voltage can be obtained as the sum of the expressions of equations (10) and (21). Since K is imaginary and the instrumentation detects the in-phase component of V, we are interested in the real part of V; that is, the imaginary part of the integral excluding the factor K. The integral is to be evaluated along the real λ-axis from $\lambda=0$ to $\lambda=\infty$. This is path A on Figure 4. Since no singularities exist in the octant enclosed by the paths A, B, and C, and since it can be shown that the integral over the infinite radius path B is zero, then the integral over path A is equal to the integral over path C. The path C is particularly advantageous because

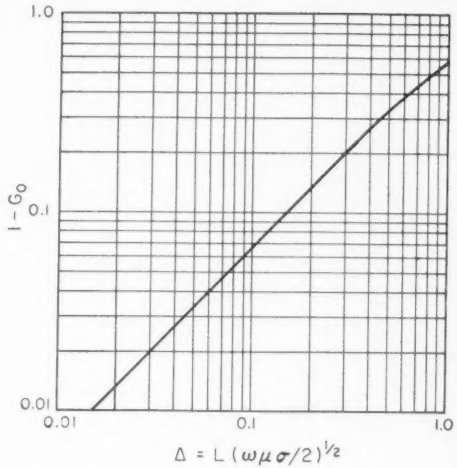

FIG. 3. Universal curve for relative response to primary excitation, G_0, that provides component σG_0 of apparent conductivity due to primary excitation.

of the symmetry with respect to the branch points $\lambda=\pm j\gamma_1$ and $\lambda=\pm j\gamma_2$. By transforming variables, $\lambda=y\sqrt{j}$ an integral expression with a real integrand except for the exponential term can be obtained. An additional change of variable given by $y^2+\omega\mu\sigma_1=x^2C^2=x^2\omega\mu(\sigma_2-\sigma_1)$, substitution for K from equation (22), and rationalization of the numerator of the integrand, provides the following result

$$V_S = \frac{\overline{K}L(\sigma_2-\sigma_1)}{l}\int_a^\infty \frac{(l\sqrt{jC^2})(x^2-a^2)}{(x+\sqrt{x^2+1})^2}\cdot\epsilon^{-l\sqrt{jC^2}}x\,dx, \tag{23}$$

where

$$\overline{K} = \frac{\omega^2\mu^2 A_R A_T I_T}{4\pi L} \tag{24}$$

$$a^2 = \sigma_1/(\sigma_2-\sigma_1) \tag{25}$$

$$C^2 = \omega\mu(\sigma_2-\sigma_1) \tag{26a}$$

$$l\sqrt{jC^2} = (1+j)l\{\omega\mu(\sigma_2-\sigma_1)/2\}^{1/2} = (1+j)\Delta_1. \tag{26b}$$

The constant $\overline{K}$ is also the coefficient of σ in equation (10).

If we define the real part of the integral of equation (23) as G_1, then the in-phase component of the induction log signal can be expressed as

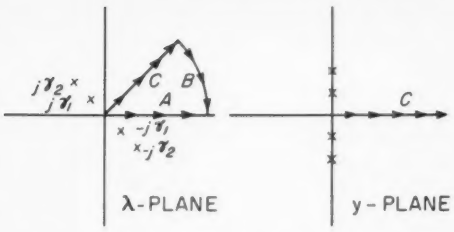

FIG. 4. Illustration of integration path C used for evaluation of integrals.

$$\text{Real Part } V = \overline{K}\{\sigma_1 G_0 + (\sigma_2 - \sigma_1)G_1 L/l\} \tag{27}$$

where G_0 is given by equation (11) and Figure 3.

The ratio of apparent and true conductivity is

$$(\sigma_A/\sigma_1) = G_0 + G_1\left(\frac{\sigma_2 - \sigma_1}{\sigma_1}\right)\frac{L}{l}. \tag{28}$$

The integral of equation (23) was programmed for digital computer computation. Results in terms of the dimensionless parameter $lC/\sqrt{2} = \Delta_1 = l\{\omega\mu(\sigma_2 - \sigma_1)/2\}^{1/2}$ are shown as Figure 5.

A similar development for the case where the sonde is located in the more conductive of the media yields

$$V_S = \frac{\overline{K}L(\sigma_1 - \sigma_2)}{l} \cdot \int_b^\infty \frac{(l\sqrt{jB^2})(x^2 - b^2)}{(x + \sqrt{x^2 - 1})^2}\epsilon^{-l\sqrt{jB^2}x}dx \tag{29}$$

$$B^2 = \omega\mu(\sigma_1 - \sigma_2)/2 \tag{30}$$

$$b^2 = \sigma_1/(\sigma_1 - \sigma_2). \tag{31}$$

The real part of the integral is defined as g_1 and

$$\sigma_A/\sigma_1 = G_0 - \left(\frac{\sigma_1 - \sigma_2}{\sigma_1}\right)g_1\left(\frac{L}{l}\right). \tag{32}$$

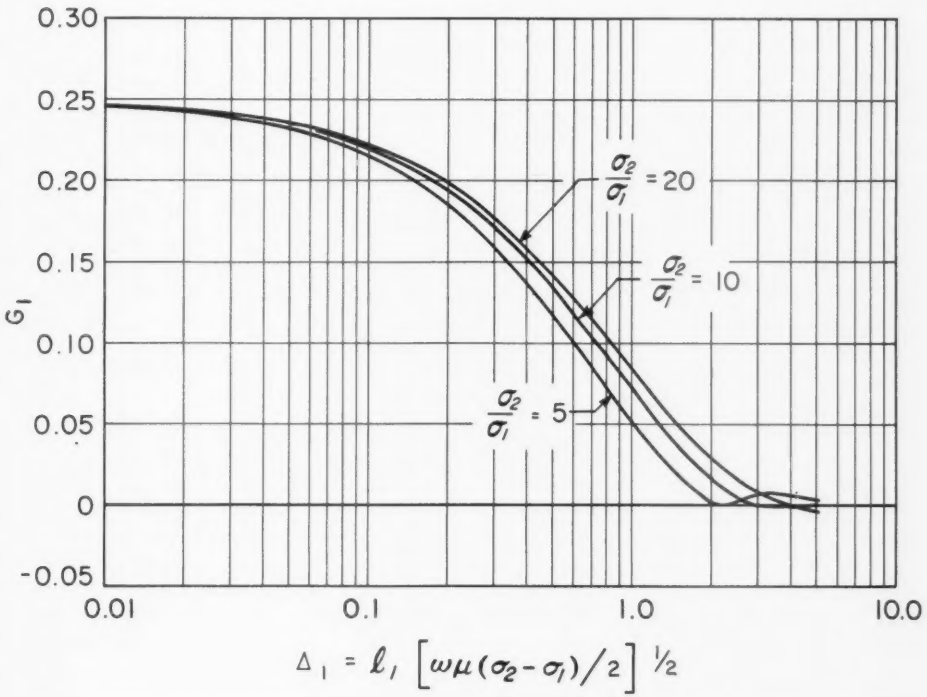

FIG. 5. Universal curve for relative response, G_1, that provides component, $(\sigma_2 - \sigma_1)G_1L/l$, of apparent conductivity due to single reflection secondary wave—$\sigma_2 > \sigma_1$.

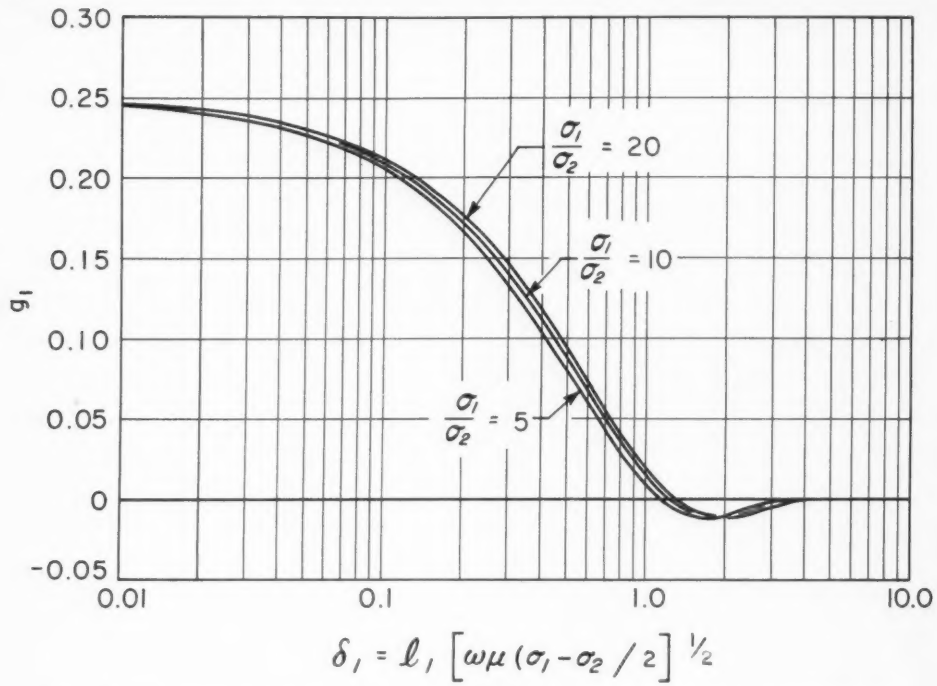

FIG. 6. Universal curve for relative response, g_1, that provides component, $(\sigma_1-\sigma_2)g_1L/l$, of apparent conductivity due to single reflection secondary wave $\sigma_1>\sigma_2$

The real part of this integral is plotted on Figure 6 as a function of the parameter

$$\delta_1 = l\{\omega\mu(\sigma_1 - \sigma_2)/2\}^{1/2} = lB/\sqrt{2}.$$

Sonde with Interface between Coils

If the interface lies between the coils as illustrated on Figure 7(a) where appropriate nomenclature is defined, the voltage is determined from Π_2 of the preceding section. Then

$$V = \frac{K}{2}\int_0^\infty \frac{2\lambda^3}{\Lambda_1 + \Lambda_2}\epsilon^{-\Lambda_2 k}\epsilon^{-\Lambda_1 h}d\lambda. \tag{33}$$

The evaluation of this integral is facilitated by rearranging in the manner shown below

$$V = X + Y \tag{34a}$$

$$X = \frac{Kh}{2L}\int_0^\infty \lambda^3\epsilon^{-\Lambda_1 L} \cdot \left\{\frac{(2\epsilon^{(\Lambda_1-\Lambda_2)k} - 1) - \Lambda_2}{\Lambda_1(\Lambda_1 + \Lambda_2)} + \frac{1}{\Lambda_1}\right\} d\lambda \tag{34b}$$

$$Y = \frac{Kk}{2L}\int_0^\infty \lambda^3\epsilon^{-\Lambda_2 L} \cdot \left\{\frac{(2\epsilon^{(\Lambda_2-\Lambda_1)k} - 1) - \Lambda_1}{\Lambda_2(\Lambda_1 + \Lambda_2)} + \frac{1}{\Lambda_2}\right\} d\lambda. \tag{34c}$$

If the approximation, $\epsilon^{(\Lambda_1-\Lambda_2)k} \doteq 1+(\Lambda_1-\Lambda_2)k$, is used, then

$$X = \frac{Kh}{2L}\left\{\int_0^\infty \frac{\lambda^3}{\Lambda_1}\epsilon^{-\Lambda_1 L}d\lambda + \int_0^\infty \frac{\lambda^3(\Lambda_1 - \Lambda_2)}{\Lambda_1(\Lambda_1 + \Lambda_2)}e^{-\Lambda_1 L}d\lambda + k\int_0^\infty \frac{2\lambda^3(\Lambda_1 - \Lambda_2)}{(\Lambda_1 + \Lambda_2)}e^{-\Lambda_1 L}d\lambda\right\} \tag{35a}$$

$$X = X_1 + X_2 + X_3. \tag{35b}$$

The real parts of X_1 and X_2 have been evaluated previously and are:

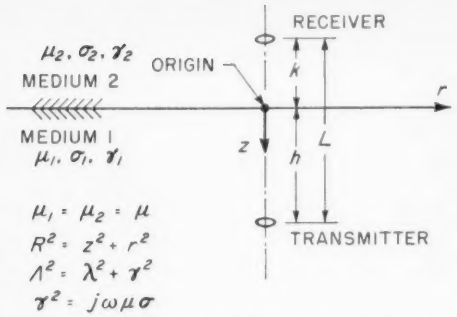

FIG. 7. Illustration and definition of symbols for analysis when coils are in different media.

$$\text{(36)}\quad \text{Real Part } X_1 = \overline{K}\sigma_1 G_0\left(\frac{h}{L}\right)$$

$$\text{(37)}\quad \text{Real Part } X_2 = \overline{K}(\sigma_2 - \sigma_1) G_1\left(\frac{h}{L}\right)$$

where G_0 and G_1 are function of $L\{\omega\mu\sigma_1/2)^{1/2}$ and $L\{\omega\mu(\sigma_2-\sigma_1)/2\}^{1/2}$, respectively, as given on Figures 3 and 5. For values of interest in induction logging, the integral X_3 can be evaluated easily by recognizing that the significant contribution to the integral is given in the region $\lambda \gg \gamma_1$ and $\lambda \gg \gamma_2$. If the numerator and the denominator radicals are expanded in series, there results

$$\text{(38)}\quad X_3 \doteq \frac{Khk}{2L}\int_0^\infty \frac{\lambda(\gamma_1^2 - \gamma_2^2)}{2}\epsilon^{-\Lambda_1 L} d\lambda.$$

The integral of this expression is

$$\text{(39)}\quad X_3 = \frac{Khk}{4L^3}(j\omega\mu)(\sigma_1 - \sigma_2)(1 + \gamma_1 L)\epsilon^{-\gamma_1 L}$$

$$\text{(40)}\quad \text{Real Part } X_3 = \overline{K}\frac{h}{L}\frac{k}{L}(\sigma_1 - \sigma_2) H(\gamma_1 L)$$

where

$$\text{(41)}\quad H(\gamma_1 L) \doteq \tfrac{1}{2}\{1 - 2\Delta_1^3 + \Delta_1^4/2 - 2\Delta_1^5/15 + \}$$

and

$$\gamma_1 L = (1+j)\Delta_1 = (1+j)\{\omega\mu\sigma_1/2\}^{1/2} L. \quad (42)$$

A similar development applies to the evaluation of Y. The induction log reading is then

$$\begin{aligned}\sigma_A = {} & \frac{h}{L}\sigma_1 G_0(\gamma_1 L) + \frac{k}{L}\sigma_2 G_0(\gamma_2 L) \\ & + \frac{h}{L}(\sigma_2 - \sigma_1) G_1(\gamma_1 L, \gamma_2 L) \\ & - \frac{k}{L}(\sigma_2 - \sigma_1) g_1(\gamma_1 L, \gamma_2 L) \\ & + \frac{h}{L}\frac{k}{L}(\sigma_2 - \sigma_1) \\ & \cdot \{H(\gamma_2 L) - H(\gamma_1 L)\}.\end{aligned} \quad (43)$$

The quantity $(1-2H) = (\Delta^3/3 - \Delta^4/4 + \Delta^5/15+)$ has, for example, a value of 6×10^{-3} for values of $L = 40$ inches, $f = 20$kc, $\sigma = 1$ mho per meter; hence, it is concluded that the correction terms $H(\gamma L)$ of equation (43) can be neglected. Then the reading can be obtained by proper weighting of the values σ_A' and σ_A'' as

$$\sigma_A = \frac{h}{L}\sigma_A' + \frac{k}{L}\sigma_A'', \quad (44)$$

where the values σ_A' and σ_A'' are the apparent conductivities with one coil at the interface and the sonde imbedded in medium 1 or medium 2, respectively.

Sonde in a Bed

Figure 2(c) defines nomenclature for the case of the sonde in a bed. The analysis of this case proceeds in the same manner as that of the preceding sections. Region 1 is divided into two sub-regions to allow convenient expression of the primary excitation. The perturbation in region 1 includes one expression for waves traveling in the positive z-direction and one for components traveling in the negative z-direction. Region 2a has components traveling in the positive z-direction and 2b has components moving in the negative z-direction. The factor $M/4\pi$ is to be inserted later.

$$\Pi_{1a} = \int_0^\infty J_0(\lambda r)\left\{\frac{\lambda}{\Lambda_1}\epsilon^{-\Lambda_1 Z} + F_a(\lambda)\epsilon^{-\Lambda_1 Z} + F_b(\lambda)\epsilon^{\Lambda_1 Z}\right\} d\lambda \quad (45a)$$

$$\Pi_{1b} = \int_0^\infty J_0(\lambda r)\left\{\frac{\lambda}{\Lambda_1}\epsilon^{\Lambda_1 Z} + F_a(\lambda)\epsilon^{-\Lambda_1 Z} + F_b(\lambda)\epsilon^{\Lambda_1 Z}\right\} d\lambda \tag{45b}$$

$$\Pi_{2a} = \int_0^\infty J_0(\lambda r)\left\{ f_a(\lambda)\epsilon^{-\Lambda_2 Z}\right\} d\lambda \tag{45c}$$

$$\Pi_{2b} = \int_0^\infty J_0(\lambda r)\left\{ f_b(\lambda)\epsilon^{\Lambda_2 Z}\right\} d\lambda. \tag{45d}$$

As before, boundary conditions at the media discontinuities, $z=h_1$ and $z=-h_2$, are $\Pi_1=\Pi_2$ and

$$\frac{\partial \Pi_1}{\partial z} = \frac{\partial \Pi_2}{\partial z}.$$

On substitution of these boundary conditions and solution of the four equations that are obtained, there results

$$F_a(\lambda) = \frac{\lambda}{\Lambda_1}\left(\frac{\Lambda_1-\Lambda_2}{\Lambda_1+\Lambda_2}\right) \cdot \frac{\left\{1+\left(\frac{\Lambda_1-\Lambda_2}{\Lambda_1+\Lambda_2}\right)\epsilon^{-2\Lambda_1 h_1}\right\}}{\left\{1-\left(\frac{\Lambda_1-\Lambda_2}{\Lambda_1+\Lambda_2}\right)\epsilon^{-2\Lambda_1 h_1}\right\}}\epsilon^{-2\Lambda_1 h_2}. \tag{46}$$

If the indicated division of braces is performed, a series expression for F_a results

$$F_a(\lambda) = \frac{\lambda}{\Lambda_1}\left(\frac{\Lambda_1-\Lambda_2}{\Lambda_1+\Lambda_2}\right)\epsilon^{-2\Lambda_1 h_2}\left\{1+\left(\frac{\Lambda_1-\Lambda_2}{\Lambda_1+\Lambda_2}\right)^2\epsilon^{-2\Lambda_1 H}+\left(\frac{\Lambda_1-\Lambda_2}{\Lambda_1+\Lambda_2}\right)^4\epsilon^{-4\Lambda_1 H}+\right\} + \frac{\lambda}{\Lambda_1}\left(\frac{\Lambda_1-\Lambda_2}{\Lambda_1+\Lambda_2}\right)^2\epsilon^{-2\Lambda_1 H}\left\{1+\left(\frac{\Lambda_1-\Lambda_2}{\Lambda_1+\Lambda_2}\right)^2\epsilon^{-2\Lambda_1 H}+\right\}. \tag{47}$$

Similarly,

$$F_b(\lambda) = \frac{\lambda}{\Lambda_1}\left(\frac{\Lambda_1-\Lambda_2}{\Lambda_1+\Lambda_2}\right)\epsilon^{-2\Lambda_1 h_1}\left\{1+\left(\frac{\Lambda_1-\Lambda_2}{\Lambda_1+\Lambda_2}\right)^2\epsilon^{-2\Lambda_1 H}+\right\} + \frac{\lambda}{\Lambda_1}\left(\frac{\Lambda_1-\Lambda_2}{\Lambda_1+\Lambda_2}\right)\epsilon^{-2\Lambda_1 H}\left\{1+\left(\frac{\Lambda_1-\Lambda_2}{\Lambda_1+\Lambda_2}\right)^2\epsilon^{-2\Lambda_1 H}+\right\}. \tag{48}$$

The receiver coil voltage can be evaluated using methods presented in preceding sections. The receiver coil voltage can be divided into components, one component for each term of the series resulting when equations (47) and (48) are substituted in equation (45a). Then,

$$V = V_P + V_1' + V_1'' + V_2' + V_2'' + V_3' + V_3'' + \quad . \tag{49}$$

The expression for these components are

$$V_P = K\epsilon^{-\gamma_1 L}(1+\gamma_1 L)/L^3 \tag{50a}$$

$$V_1' = \frac{K}{2}\int_0^\infty \frac{\lambda^3}{\Lambda_1}\cdot\left(\frac{\Lambda_1-\Lambda_2}{\Lambda_1+\Lambda_2}\right)\epsilon^{-\Lambda_1(L+2h_2)}d\lambda \tag{50b}$$

$$V_1'' = \frac{K}{2}\int_0^\infty \frac{\lambda^3}{\Lambda_1}\cdot\left(\frac{\Lambda_1-\Lambda_2}{\Lambda_1+\Lambda_2}\right)\epsilon^{-\Lambda_1(2h_1-L)}\,d\lambda$$

$$V_2' = \frac{K}{2}\int_0^\infty \frac{\lambda^3}{\Lambda_1} \tag{50c}$$

$$\cdot\left(\frac{\Lambda_1-\Lambda_2}{\Lambda_1-\Lambda_2}\right)^2\epsilon^{-\Lambda_1(2H+L)}d\lambda \tag{50d}$$

$$V_n = \frac{K}{2}\int_0^\infty \frac{\lambda^3}{\Lambda_1} \cdot \left(\frac{\Lambda_1 - \Lambda_2}{\Lambda_1 + \Lambda_2}\right)^n \epsilon^{-\Lambda_1 l_n} d\lambda. \tag{50e}$$

It is of interest to note the meaning of distances such as $(L+2h_2)$. These distances are recognized as the distance the wave propagates with reflection at each interface. The ratio $(\Lambda_1-\Lambda_2)/(\Lambda_1+\Lambda_2)$ represents the reflection coefficient at each interface. Thus,

$$l_1' = 2h_2 + L, \quad l_1'' = 2h_1 - L,$$
$$l_2' = 2H + L, \quad l_2'' = 2H - L, \text{ etc.}$$

The receiver voltage in phase with the transmitter current is derived from the real parts of the integral expressions of equation (50). The apparent conductivity to true conductivity ratio is given as

$$\frac{\sigma_A}{\sigma_1} = G_0 + \left(\frac{\sigma_2 - \sigma_1}{\sigma_1}\right) \cdot \left\{\frac{G_1'L}{l_1'} + \frac{G_1''L}{l_1''} - \frac{G_2'L}{l_2'} - \frac{G_2''L}{l_2''} + \frac{G_3'L}{l_3'} + \frac{G_3''L}{l_3''} + \right\}. \tag{51}$$

The factors G_0, G_1' and G_1'' are plotted as Figure 3 and Figure 5, respectively. The factors for multiple reflections were computed from a transformed version of equation (50e); namely,

$$V_n = (-1)^n \left(\frac{K}{2}\right)(jC^2) \cdot \int_a^\infty \frac{(jC^2)^{1/2}(x^2 - a^2)}{(x + \sqrt{x^2+1})^{2n}} e^{-l_n\sqrt{jC^2}} x dx \tag{52}$$

where a and C are given by equation (25) and (26). For values of $n>1$, an excellent approximation for our purposes results from using

$$(x + \sqrt{x^2+1})^{-2n} \doteq \epsilon^{-2nx}.$$

The resulting integral is evaluated easily and results are shown as Figure 8 and Figure 9 for 2 and 3 reflections, respectively.

DISCUSSION OF RESULTS

Results obtained in the preceding analysis can be compared with the geometric factor results of Doll. The geometric factor analysis assumes negligible far field. With this assumption Doll expressed the receiver coil voltage in-phase component as

$$V = \frac{\overline{K}}{L}\int_{-\infty}^{\infty}\int_0^\infty \sigma(r,z)g(r,z)drdz \tag{53}$$

$$\overline{K} = \omega^2\mu^2 A_R A_T I_T/4\pi. \tag{54}$$

The factor $g(r, z)$ is the geometric factor defined by Doll and evaluated as

$$g(r,z) = \frac{L}{2}\frac{r^3}{R_1^3 R_2^3}. \tag{55}$$

It can be shown that

$$\int_{-\infty}^{\infty}\int_0^\infty g(r,z)drdz = 1. \tag{56}$$

In discussing response attributed to conducting beds where conductivity is independent of r, it has been found useful to define a second geometric factor

$$G(z) = \int_0^\infty g(r,z)dr = \begin{cases} 1/2L, & |z| < L/2 \\ L/8z^2, & |z| > L/2 \end{cases}, \tag{57}$$

so that

$$V = \frac{\overline{K}}{L}\int_{-\infty}^{\infty}\sigma(z)G(z)dz. \tag{58}$$

It can be shown that if a two-coil sonde is imbedded in a semi-infinite medium of conductivity σ_1 with the interface with a second semi-infinite medium of conductivity σ_2 a distance $l/2$ from the sonde center as depicted in Figure 2(b), the geometric factor of Doll gives the result

$$\left(\frac{\sigma_A}{\sigma_1}\right) = 1 + 0.25\left(\frac{\sigma_2 - \sigma_1}{\sigma_1}\right)\frac{L}{l}. \tag{59}$$

This equation should be compared with equation (28) which for the same geometry gives

$$\left(\frac{\sigma_A}{\sigma_1}\right) = G_0 + G_1\left(\frac{\sigma_2 - \sigma_1}{\sigma_1}\right)\frac{L}{l}, \tag{60}$$

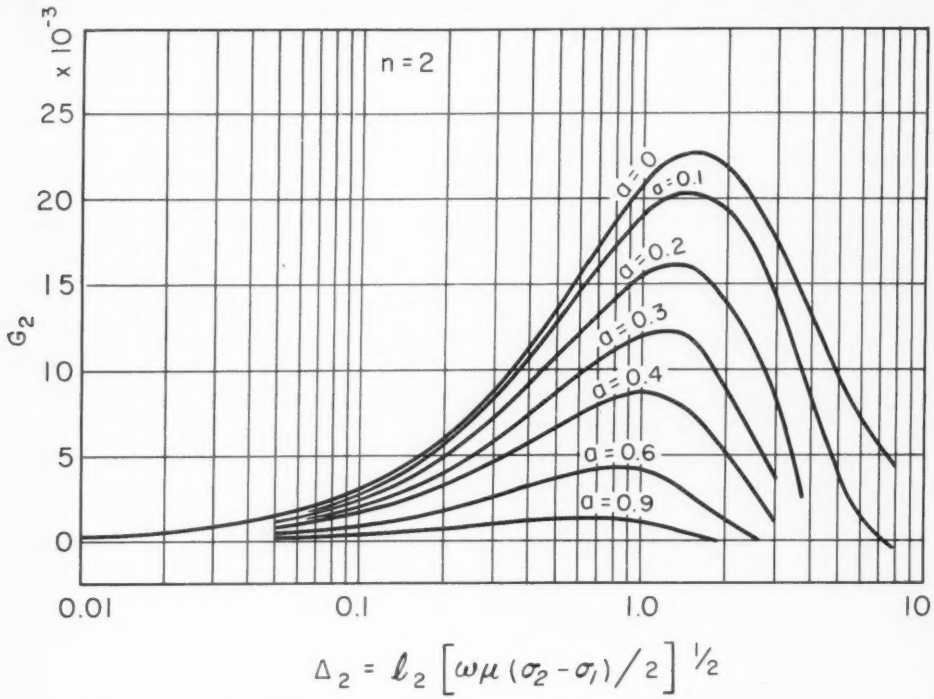

FIG. 8. Universal curve for relative response, G_2, that provides component, $(\sigma_2-\sigma_1)G_2L/l_2$, of apparent conductivity due to double reflection wave—$\sigma_2>\sigma_1$.

where G_0 and G_1 are functions of $L\{\omega\mu\sigma_1/2\}^{1/2}$ and $l\{\omega\mu(\sigma_2-\sigma_1)/2\}^{1/2}$, respectively, given as Figures 3 and 5. Similarly, for the sonde in a bed as depicted in Figure 2(c), the geometric factor gives a result.

$$(61)\qquad \left(\frac{\sigma_A}{\sigma_1}\right) = 1 + 0.25\left(\frac{\sigma_2-\sigma_1}{\sigma_1}\right)\cdot\left(\frac{L}{l_1'}+\frac{L}{l_1''}\right)\cdot$$

This result should be compared with equation (51) where

$$(62)\qquad \left(\frac{\sigma_A}{\sigma_1}\right) = G_0 + \left(\frac{\sigma_2-\sigma_1}{\sigma_1}\right)\cdot\left\{\frac{G_1'L}{l_1'}+\frac{G_1''L}{l_1''}-\frac{G_2'L}{l_2'}-\frac{G_2''L}{l_2''}+\frac{G_3'L}{l_3'}+\frac{G_3''L}{l_3''}+\right\}$$

with G_1', G_1'', G_2', G_2'' etc., as given by Figures 5, 8 and 9.

Tixier, Alger, and Tanguy have presented curves of an integrated vertical geometric factor for thin beds with "skin-effect" considered; however, details of the analysis are not included. Neither is an exact definition of this vertical geometric factor stated although, presumably, the calibration constant of the coil system is selected for correct reading in the more conductive material. Then,

$$\sigma_A = \sigma_1 G_v + \sigma_2(1-G_v) \qquad (63)$$

where G_v is the integrated vertical geometric factor. It follows that G_v defined in this manner is a function of G_0, G_1, G_2, etc. as well as bed thickness, as given by equation (62), and it is influenced by shoulder conductivity and contrast σ_2/σ_1.

Since the induction log is primarily a conductivity sensing device, highly conductive adjacent beds may produce more signal than the bed in which the sonde resides. The geometric factor

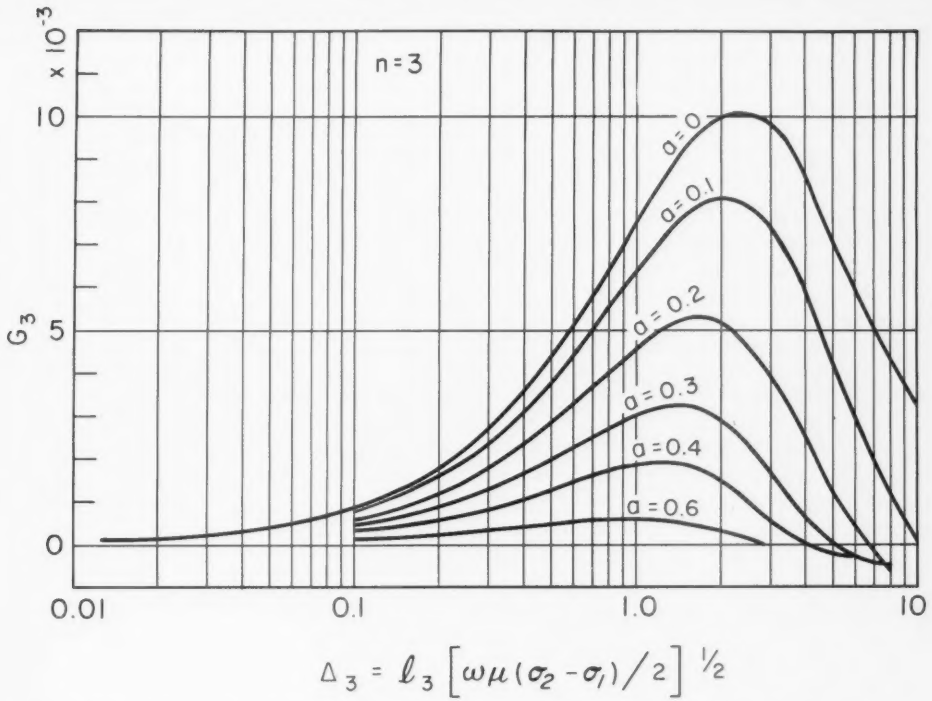

FIG. 9. Universal curve for relative response, G_3, that provides component, $(\sigma_2-\sigma_1)G_3L/I_3$, of apparent conductivity due to triple reflection wave—$\sigma_2>\sigma_1$.

concept gives too much apparent importance to media located some distance from the sonde. This conclusion results from the above comparisons since $G_1<0.25$. Thus, the effect of the attenuation considered in this paper is to give more and proper weight to the formation material in the near vicinity of the sonde. These results take on additional importance when it is realized that induction log sondes utilize focus coil arrangements. These focus coils can be designed such that the coil system has excellent response for beds immediately adjacent the sonde, the response to beds more distant from the coil system being minimized by the attenuation effect.

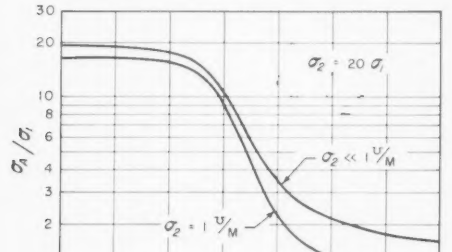

FIG. 10. Example response of a 40 inch two coil system in the vicinity of an interface separating media having contrast $\sigma_2/\sigma_1=20$.

Example response curves for 2-coil and 4-coil sondes are shown as Figures 10 and 11. The 2-coil sonde considered had a coil spacing $L=40$ inches. The 4-coil sonde had a main coil spacing of $L=40$ inches with focus coils 25 inches from the main coils and with a ratio of main coil turns to focus coil turns of $N/n=8.2$. The turns ratio was selected such that mud column effect would be minimized; i.e. the contribution to the reading by formation material in the vicinity of the axis was minimized. Results of analysis utilizing the geometric factor approach of Doll is shown for

purpose of comparison. The importance of the "propagation-effect" when high conductivity material is present is to be noted. The curves obtained from the geometric factor analysis hold only when

$$L\left\{\omega\mu(\sigma_2 - \sigma_1)\right\}^{1/2} \ll 1.$$

Careful comparison with the results of Tixier cannot be made since the geometry of the coil systems is not specified. Comparison of the coil system response curves of Tixier with those of Figure 11 is not the subject of the present paper; however, the following brief comments can be made. If the bed response of the example 4-coil system of Figure 11 is computed and compared with bed response computed from the published integrated vertical geometric factor of Tixier using equation (63), then the following is indicated. The 4-coil system reads 31 percent low in 1 ohm-meter material and 5 percent low in 0.05 ohm-meter material while the Tixier curves give 0 percent low reading in 1 ohm-meter and approximately 35 percent high reading in 0.05 ohm-meter material; this difference is explained by the difference in multiplicative scale constant. At bed thickness of 80 inches and contrast of shoulder conductivity of 1 mho/meter and bed conductivity of 0.05 mho/meter, the example 4-coil system indicates conductivity 30 percent high and the Tixier curves indicate a reading 40 percent low which merely indicates a greater degree of focus for the latter coil system.

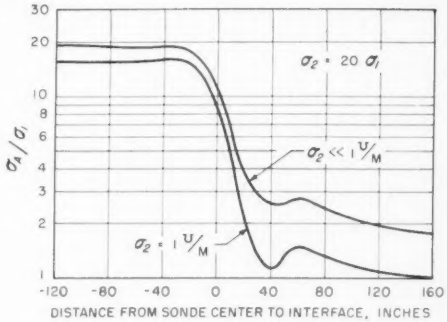

FIG. 11. Example response of a four coil system in the vicinity of an interface separating media having contrast $\sigma_2/\sigma_1 = 20$.

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INDUCED POLARIZATION IN ELECTROLYTE SATURATED EARTH PLUGS*

J. H. HENKEL† AND T. C. COLLINS‡

Abstract: This paper describes the results of some studies of the dependence of induced polarization and of the formation resistivity factor upon solution concentration in saturated porous plugs. Two theories based upon two different simple models are developed. The first treats induced polarization as an electric dipole polarization occurring at the surface of clay particles. It is a relaxation theory that does not lead to results agreeable with experiments. The second theory treats induced polarization as a concentration polarization which is induced at solution-clay surfaces when current flows across the surfaces. The second theory is more successful than the first in two ways: (1) it leads to a time dependence more consistent with the experimental decays; (2) it leads to equations involving the resistivity of the saturating solution ρ_s which are also more consistent with experiments.

INTRODUCTION

The work reported in this paper was undertaken to develop theoretically and test experimentally the similarities between: (1) the dependence of the formation resistivity factor F upon the resistivity ρ_s of the saturating solution, and (2) the dependence of the induced polarization IP upon the resistivity of the saturating solution. In the theoretical development two simple models are assumed. The first model assumes that electric dipoles are associated with clay particles in electrolytic solution.[1] The second model assumes that the clay particles are electrically conducting particles and that electrical conduction in a saturated plug is equivalent to one in which a solution region is in parallel with a combination clay region-solution region in series as indicated in Figure 4.

DIPOLE LAYER MODEL

It is assumed that clay particles have charged surfaces which are in contact with an electrolytic solution and that the electric fields arising from the charged surfaces give rise to polarized layers of molecules adjacent to the surfaces. This is illustrated in Figures 1 and 2 diagrammed below. Upon the application of an external electric field, the total fields at the clay surfaces change and subsequently the polarization of the polarized layers changes.

The introduction of a change in the external electric field at a clay surface causes the temperature T_s of the system of polarized molecules to change. Let $\theta = T - T_s$, where T is the temperature of the rest of the system assumed to be constant. A non-zero θ gives rise to an energy transfer, and as long as θ is not large, the transfer may be written as:

$$dQ = -\alpha(x)\theta dt, \qquad (1\text{-}1)$$

where dQ is the heat energy transferred from polarized molecules to the rest of the system in the time dt. The constant $\alpha(c)$ is defined as the coefficient of heat contact between the polarized layer and the rest of the system and depends upon the concentration c of the solution.

The first law of thermodynamics for the polarized system may be written in the form

$$dQ = C_E\left(\frac{\partial T}{\partial P}\right)_E dP + C_p\left(\frac{\partial T}{\partial E}\right) dE, \quad (1\text{-}2)$$

where P is the dipole polarization, E is the electric field intensity and C_p and C_E are the specific heats at constant P and E, respectively.

For steady state sinusoidal currents:

[1] The electric dipole model is discussed to show that it disagrees with experiment in more ways than one.

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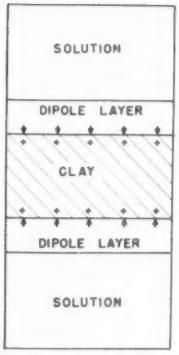

FIG. 1. Dipole layer model before current pulse.

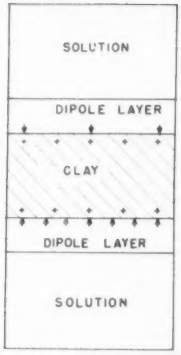

FIG. 2. Dipole layer model during and shortly after current pulse.

$$E(t) = E_0 e^{i\omega t} \tag{1-3}$$

$$P(t) = P_0 e^{i\omega t} \tag{1-4}$$

$$\theta(t) = \theta_0 e^{i\omega t}. \tag{1-5}$$

Here both E_0 and P_0 are complex, so that E and P are not necessarily in phase with each other. Thus, equations (1–1) and (1–2) become

$$\frac{dQ}{dt} = -\alpha\theta_0 e^{i\omega t} \tag{1-6}$$

$$\frac{dQ}{dt} = C_E\left(\frac{\partial T}{\partial p}\right)_E \frac{dP}{dt} + C_p\left(\frac{\partial T}{\partial E}\right)_p \frac{dE}{dt}. \tag{1-7}$$

Combining equations (1–3) through (1–7) it follows that

$$-\alpha\theta_0 = i\omega\left[C_E\left(\frac{\partial T}{\partial P}\right)_E P_0 + C_p\left(\frac{\partial T}{\partial E}\right)_p E_0\right]. \tag{1-8}$$

Treating θ_0, P_0 and E_0 as differentials, we may write

$$\theta_0 = \left(\frac{\partial T}{\partial P}\right)_E P_0 + \left(\frac{\partial T}{\partial E}\right) E_0. \tag{1-9}$$

Equations (1–8) and (1–9) lead to

$$\frac{P_0}{E_0} = \left(\frac{\partial P}{\partial E}\right)_T \left[\frac{1 + i\dfrac{\omega C_p}{\alpha}}{1 + i\dfrac{\omega C_E}{\alpha}}\right]. \tag{1-10}$$

Here $(\partial p/\partial E)_T$ is defined as the static susceptibility χ_0 and P_0/E_0 the susceptibility χ so that[2]

$$\chi(\omega) = \chi_0\left[\frac{1 + i\dfrac{\omega C_p}{\alpha}}{1 + i\dfrac{\omega C_E}{\alpha}}\right]. \tag{1-11}$$

For currents other than sinusoidal, the current can be represented by a Fourier integral (or sum) of sinusoidal currents; i.e., the electric field may be written as:

$$E(t) = \int_{-\infty}^{\infty} A(\omega) e^{i\omega t} d\omega, \tag{1-12}$$

where

$$A(\omega) = \frac{1}{2\pi}\int_{-\infty}^{\infty} E(t) e^{-i\omega t} dt. \tag{1-13}$$

The polarization P would be given by the following integral:

[2] This equation can be derived by assuming other models, such as by assuming that clay particles themselves are the electric dipoles.

$$(1\text{-}14)\quad P(t) = \int_{-\infty}^{\infty} \chi(\omega) A(\omega) e^{i\omega t} d\omega.$$

The evaluation $A(\omega)$ for the bi-directional square pulses as shown in Figure 3 which were used in the experimental studies leads to:

$$(1\text{-}15)\quad A = \sum_{n=0}^{\infty} A_n(\omega) = \frac{1}{2\pi}\int_{-\tau_1}^{0} E_0 e^{-i\omega t} dt - \frac{1}{2\pi}\int_{-3\tau_1}^{-2\tau_1} E_0 e^{-i\omega t} dt + \int_{-5\tau}^{-4\tau} E_0 e^{-i\omega t} dt - \cdots$$

$$(1\text{-}16)\quad P(t) = \chi_0 \int_{-\infty}^{\infty} \frac{1 + i(\omega C_p/\alpha)}{1 + i(\omega C_E/\alpha)} \sum_{n=0}^{\infty} A_n(\omega) e^{i\omega t} d\omega$$

$$(1\text{-}17)\quad \chi = \frac{P}{E_0} = \left[\sum 2(-1)^n \chi_0 \frac{C_E - C_p}{C_E} e^{-2nt_1(\alpha/C_E)}\right] \times \left[1 - e^{-t_1(\alpha/C_E)}\right] e^{-t\alpha/C_E},$$

where t_1 is the time duration that the current was on and also the time duration that the current was off. In equation (1–17) the time t after the last current pulse, enters only in the last factor $e^{-t\alpha/C_E}$. This means that the decay constant is proportional to α.

For just a single current pulse of duration t_1, equation (1–17) becomes

$$(1\text{-}18)\quad \chi = K\left[1 - e^{-t_1\alpha/C_E}\right] e^{-t\alpha/C_E},$$

where $K = 2\chi_0(C_E - C_p)/C_E$.

ELEMENTARY CLAY CONDUCTOR MODEL

In the second theory the main assumption is that the current flows across clay-solution boundaries. A simple cellular model is used to represent the soil sample (see Figure 4). This model follows indirectly from the conclusions of Patnode and Wyllie (1950). It is assumed that a cell consists of a solution region and a clay region as shown in Figure 4. It is also assumed that the current can take one of two paths through a cell: (1) through solution only, or (2) through solution, across a clay-solution boundary, and through clay.

The relation for the formation resistivity factor vs solution resistivity becomes

$$F = \frac{\rho_s + B}{\rho_s C + D}, \qquad (2\text{-}1)$$

where B, C, and D are factors which edpend upon cell dimensions and the resistivity of the clay particles.

According to Henkel and Van Nostrand (1957) the polarization induced at a solution-conductor boundary is inversely proportional to effective electrolyte concentration and proportional to current density; i.e.,

$$V_{op} = g I_{cs} \rho_s, \qquad (2\text{-}2)$$

where I_{cs} is the normal current density flowing across the conductor-solution surface, g is a constant of proportionality and V_{0p} is the out of phase potential (time of no current flow) in the soil sample. Using (2–2) and Figure 4 it follows that

$$\frac{V_{op}}{V_{1p}} = \frac{H\rho_s}{\rho_s + B}, \qquad (2\text{-}3)$$

where V_{1p} is the potential difference across the earth plug during the time of current flow and H

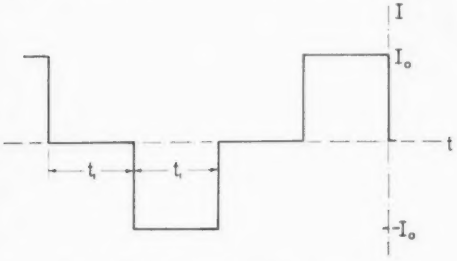

FIG. 3. Bi-directional square current pulse (t_1=0.25 sec.).

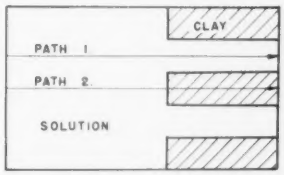

FIG. 4. Parallel resistor model of soil sample.

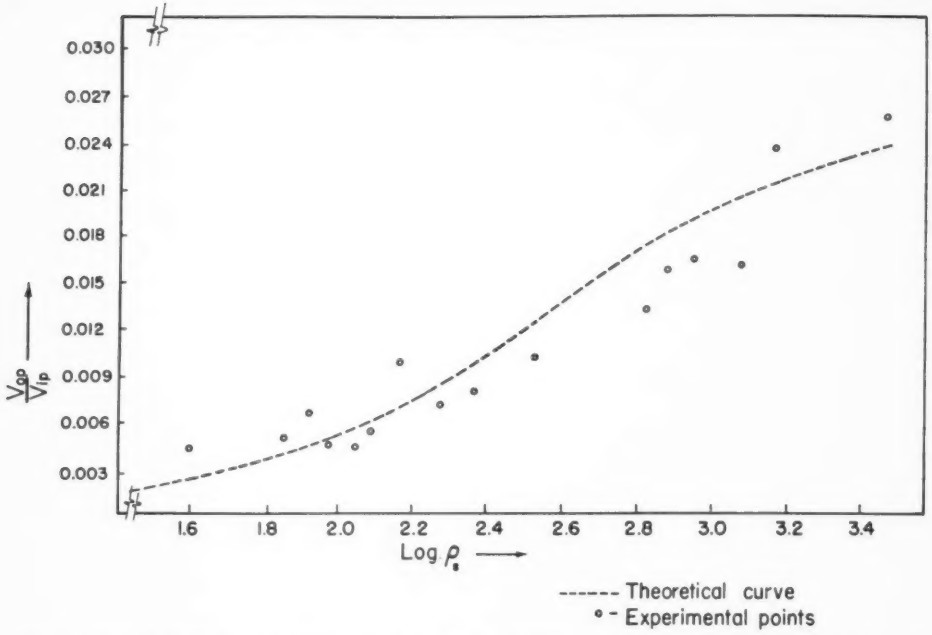

FIG. 5. Graph of ratio of out-of-phase voltage to in-phase voltage ($t=0$ and $t_1=0.25$ sec) versus log ρ_s (ρ_s in ohm-cm). Theoretical curve computed from equation 2-3 and experimental values from soil sample No. 56 saturated with varying solutions of Na Cl(.005N–.5N).

is a constant. (Note that the denominator of equation (2–3) is the same as the numerator in equation (2–1).)

EXPERIMENTAL STUDIES OF IP VERSUS SOLUTION CONCENTRATION IN POROUS PLUGS

Earth plugs obtained from the Field Research Laboratories of the Magnolia Petroleum Company were saturated with solutions of NaCl of various concentrations (.005N–.5N). Bi-directional square wave pulses as shown in Figure 3 were passed through saturated plugs and electrical responses using standard 4 electrode arrangements were observed on an oscilloscope.

Figure 5 shows the dependence of the experimental values of V_{0p}/V_{1p} (at time $t=0$) upon the resistivity of the saturating solution for a typical plug. Figure 5 also shows a plot of equation (2–3) fitted to these points.

Figure 6 shows the experimental dependence of the formation resistivity factor upon ρ_s for the same plug and also a plot of equation (2–1) fitted to these points. The constant B used in the fit was the same as that used in Figure 5.

DISCUSSION OF RESULTS

It seems reasonable to assume that the coefficient of heat contact in equation (1–1) is a linear function of the electrolyte concentration. Assuming that α is proportional to the effective solution concentration (i.e., proportional to $1/\rho_s$), the relationship between the ratio of the induced polarization at time $t=0$ to the electric field intensity versus the resistivity of the saturating solution as given by equation (1–18) approaches a constant at high concentrations or low resistivities and approaches zero at low concentrations or high resistivities, the opposite of the experimental data (see Figure 5). In order to obtain the general slope shown in Figure 5, it is necessary to assume that α is inversely proportional to the solution concentration, which seems unreasonable to the authors. However, according to Collett and Wait (1959) the induced polarization does decrease with increasing electrolyte concentration for large concentrations (>.01N) but not for very weak concentrations; i.e., Collett found that there was an optimum concentration which gave the largest

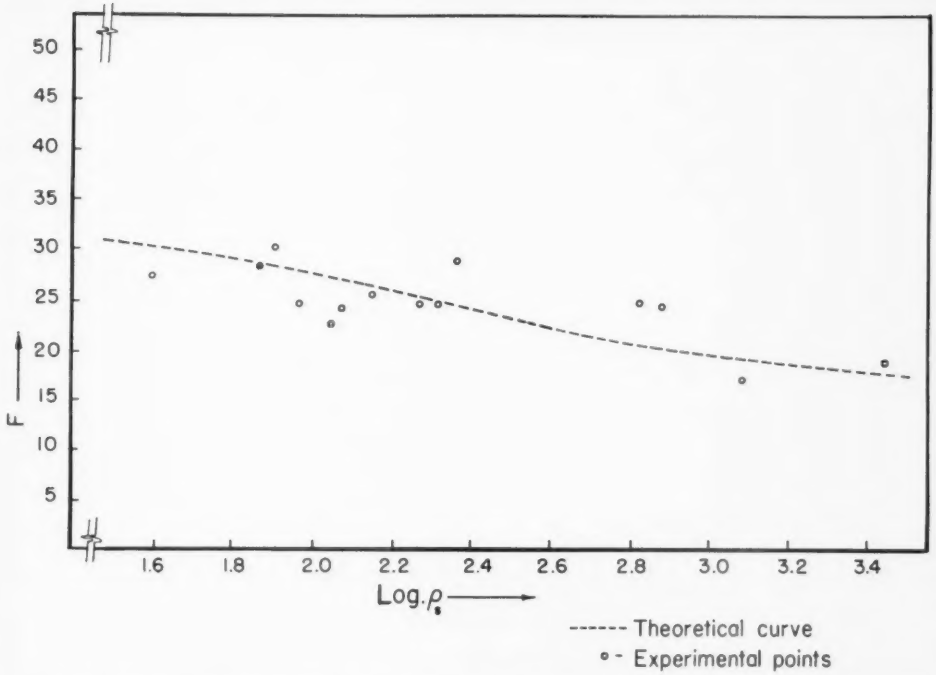

Fig. 6. Graph of F versus log ρ_s (ρ_s in ohm-cm). Theoretical curve computed from equation 2-1 and experimental values from soil sample No. 56 saturated with varying solutions of Na Cl(.005N–.5N).

induced polarization ratio V_{0p}/V_{1p}. Mr . Hunter (1959), also found that there was an optimum concentration and this led to the following statement presented to the 1959 Southeastern Section of the American Physical Society Meeting by Henkel:

"The phenomenon of electrical polarization induced in electrolyte saturated earth sample by electric currents is similar in many respects to the phenomenon of the anomalous absorption of sound by gases; i.e., (1) there is an optimum frequency and electrolyte concentration for which the induced polarization is a maximum, (2) the dependence of induced polarization upon clay content in soil samples is very similar to the dependence of the sound absorption coefficient in air upon humidity." Later repeat tests by the present authors failed to show that there was a nonzero optimum concentration. The optimum concentrations found by Collett and by Hunter occur at low concentrations ($\sim$.01N). The present authors found that at low concentrations experimental results were hard to duplicate and, therefore, they believe that these low concentration results are unreliable.

Van Nostrand and Henkel 1957 discussed the time dependence of the polarization decay in their paper and they indicated that induced polarization did not decay exponentially as equation 1–17 indicates but decays according to that based upon diffusion. Marshall and Madden (1959) also indicate that the diffusion phenomenon is the most important factor contributing to induced polarization.

There was a spread in the experimental values for the formation resistivity factors (F) and thus the fit of equation (2-1) to the experimental data was a rather rough one. However, there is a general fit indicating that the cellular model is certainly better than the electric dipole model. Thus, this paper gives added support to the conclusion of other papers (Van Nostrand and Henkel 1957, Bliel 1953, Marshall and Madden 1959) that induced polarization can be explained better in

terms of electrical conducting earth particles than in terms of relaxation of electric dipole polarization.

The models presented in this paper are, indeed, simple ones and do not contain as many parameters as those of Marshall and Madden (1959) or as those of Wait (1959). Consequently the models presented in this paper are not as flexible and can not be fitted to experiment curves as well as those of Wait and Marshall and Madden. Also, the assumption of straight current paths as shown in Figure 4 is weak, but after this assumption is made no added restrictions on the relative volume of the conducting clay regions are introduced. This is to be compared with Wait's treatment in that he did not assume straight current paths but did assume that his dielectric coated conducting particles were small.

Assuming the validity of the clay conduction cellular model, it follows that a similarity between the dependence of F upon ρ_e and IP upon ρ_e is given by the term (ρ_e+B) in (2-1) and (2-3).

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GEOPHYSICS, VOL. XXVI, NO. 2 (APRIL, 1961), PP. 211–228, 15 FIGS.

THE DIURNAL PROBLEM IN AEROMAGNETIC SURVEYING IN CANADA*

K. WHITHAM† AND E. R. NIBLETT†

Abstract: Errors introduced into aeromagnetic survey results because of geomagnetic time variations have been analyzed in two ways. In the first, statistical properties of average magnetic disturbance have been calculated for five locations well distributed in latitude in Canada. The autocorrelation functions of vertical magnetic field fluctuations have been used to estimate errors in aeromagnetic surveying as a function of the length of the base loop and the length of the traverse lines or profiles, for five latitudes. In practical applications, the r.m.s. errors are proportional to the square root of elapsed time. These results can be explained in terms of the shape of the autocorrelation functions, and models of disturbance which might produce them are discussed.

In the second part experimental results are presented of a comparison of total field intensity fluctuations measured with recording proton precession magnetometers at two pairs of stations, one pair 26 miles apart and the other 94 miles apart. The measurements were taken in Western Canada south of the auroral zone. The r.m.s. differences in the time variations have been determined quantitatively for each hour for both pairs of stations; statistically, it was found that these differences were proportional to the r.m.s. level of magnetic activity and, in this region, to the separation of the stations. The frequency distributions of the r.m.s. differences between the two pairs of stations for the month of September 1959 have been determined.

A comparison of the indirect and direct methods of correction indicates that scientifically, in this region, there is little to choose between them in terms of accuracy. Operational considerations are mentioned.

INTRODUCTION

An account has been given previously (Whitham and Loomer, 1957) of the general problems involved in compensating aeromagnetic data in northern Canada for external transient changes in the earth's magnetic field—the so-called "high latitude diurnal problem." The main features of the changes with latitude in the diurnal variation of the shorter period irregular magnetic activity in northern Canada were described. As a result of a simple statistical analysis of the changes in magnetic field intensity at Baker Lake, N.W.T., it was suggested that errors of about one-half the diurnal correction between base lines should appear in individual profiles using customary magnetic control flight procedures, and that because of the random nature of the disturbance, an improvement of some forty percent only in accuracy is produced by doubling the base looping used. In this earlier paper it was also suggested that the statistical approach to the indirect method of correction could perhaps be usefully extended using correlogram methods.

Such an investigation is now presented using a sample of homogeneous data from five Canadian observatories, situated between 48 degrees N and 75 degrees N. The variations of both base-loop errors and traverse errors as a function of latitude and elapsed time or the length of these lines, are deduced. The random nature of the non-linear component of irregular disturbance is confirmed at all latitudes; and simple formulae are deduced for the prediction of errors if the r.m.s. changes in magnetic field intensity in time are available from a nearby observatory or base-station.

Under average conditions, the errors are sufficiently large with reasonable control patterns to make worthwhile reconsideration of the validity of correcting directly from a base-station. The results of an experiment, employing recording proton-precession magnetometers in station pairs in western Canada, have been analyzed quantitatively. It was found, in this region, that the r.m.s. differences in total intensity field fluctuations were proportional to the r.m.s. level of magnetic activity and to the separation of the stations. Using quickly determined indices of magnetic activity, it was then possible to compare

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directly the accuracy of the direct and indirect approaches.

Morley (1953), Reford (1958) and Hoylman (1958, 1959) have previously considered the direct approach with somewhat contradictory qualitative conclusions. None of these authors handled the statistical problem quantitatively nor supplied the necessary data for reasonable extrapolation or assessment of operational practicability. This paper attempts to supply this information.

THE INDIRECT APPROACH

The Magnetic Data Analyzed

Because of the large amount of computing necessary to determine correlograms by hand methods from photographic magnetograms, the data analyzed were limited to three days in August, 1957, selected so as to be as representative as possible of average magnetic conditions. This selection was made by visual examination and checked by means of the K-index daily sums available at the time of selection (March 1958) from Meanook and Victoria magnetic observatories only. Table I illustrates the average nature of the three selected days, August 1, 2 and 20, 1957, and shows in addition the planetary K-index, Kp, and amplitude index, Ap, data which became available after the commencement of this work (CRPL-F158 Part B, Solar-Geophysical Data). At one observatory, Baker Lake, N.W.T., the record for August 20 was replaced by that for August 4 because of the former's poor photographic quality. Otherwise the data are homogeneous and none of the selected days appeared in the list of five international quiet or disturbed days for the month (see reference above). It is believed therefore that the days are representative of the level of activity during one-half to two-thirds of the month.

TABLE I. SUMMARY OF MAGNETIC CHARACTERISTICS OF SELECTED DAYS

Date	Meanook $\sum K$ day	Victoria $\sum K$ day	$\sum K_p$ day	$\overline{A}_p$ (units 2 gamma)
Aug. 1, 1957	14	20	14−	6
Aug. 2, 1957	15	17	17○	9
Aug. 20, 1957	18	18	18−	10
Mean, Aug., 1957	16.7	19.0		14
Aug. 4, 1957	16	20	15+	12

The photographic magnetograms available from five Canadian observatories (Victoria, Meanook, Yellowknife, Baker Lake and Resolute Bay) consist of two orthogonal horizontal intensity records together with a vertical field intensity record. At moderate-to-high latitudes $\Delta F \doteqdot \Delta Z$ and the vertical fluctuations provide a first approximation to the total field intensity perturbations. The mean scale value of the Z magnetograms for the five observatories was 6.4 gammas/mm; the maximum sensitivity (Victoria) was 3.3 gammas/mm. and the minimum (Meanook) was 11.1 gammas/mm.

The Autocorrelation Functions

The magnetograms from five observatories were scaled in mm. for each day every 2.5 minutes of time. The data in each two-hour universal time interval were made stationary (sum = 0) by subtracting the appropriate linear correction obtained by extrapolating and interpolating from the two one-hourly mean values in each interval. The autocorrelation of each sample is defined

$$r(k) = \lim_{h\to\infty} \int_{-h}^{h} Z(t)\cdot Z(t+2.5k)dt/2h$$
$$= \overline{Z(t)\cdot Z(t+2.5k)}$$

the bar denoting an average over all t. From the stationary series, expressed in mm., $r(0)$, $r(1)$, $r(2)$, $r(4)$, $r(6)$, $r(8)$, $r(16)$ and $r(24)$ were calculated in mm.^{2}, and then converted to gammas^2 using the appropriate scale value. In general, plots of $r(k)$ against k are similar, but diurnal changes in activity produce large changes in the amplitude of the autocorrelograms. Figure 1 shows typical autocorrelograms for the six two-hourly periods nearest local noon (the day-time sets) on August 2, 1957 at Meanook observatory, Alberta. Figure 2 shows the results of averaging these six periods for this day, and the corresponding averages on the other two days.

It is shown later that a convenient parameter for defining the variation in amplitude is $r(0)^{1/2}$. Table II indicates the ratio of maximum-to-minimum values of this parameter for the six day-time autocorrelograms and for the remaining six night-time autocorrelograms, for each day for each observatory. In addition in the last two columns the variations of this ratio for the three daily means are given, both for the mean of the six day-time sets and for that of the six night-

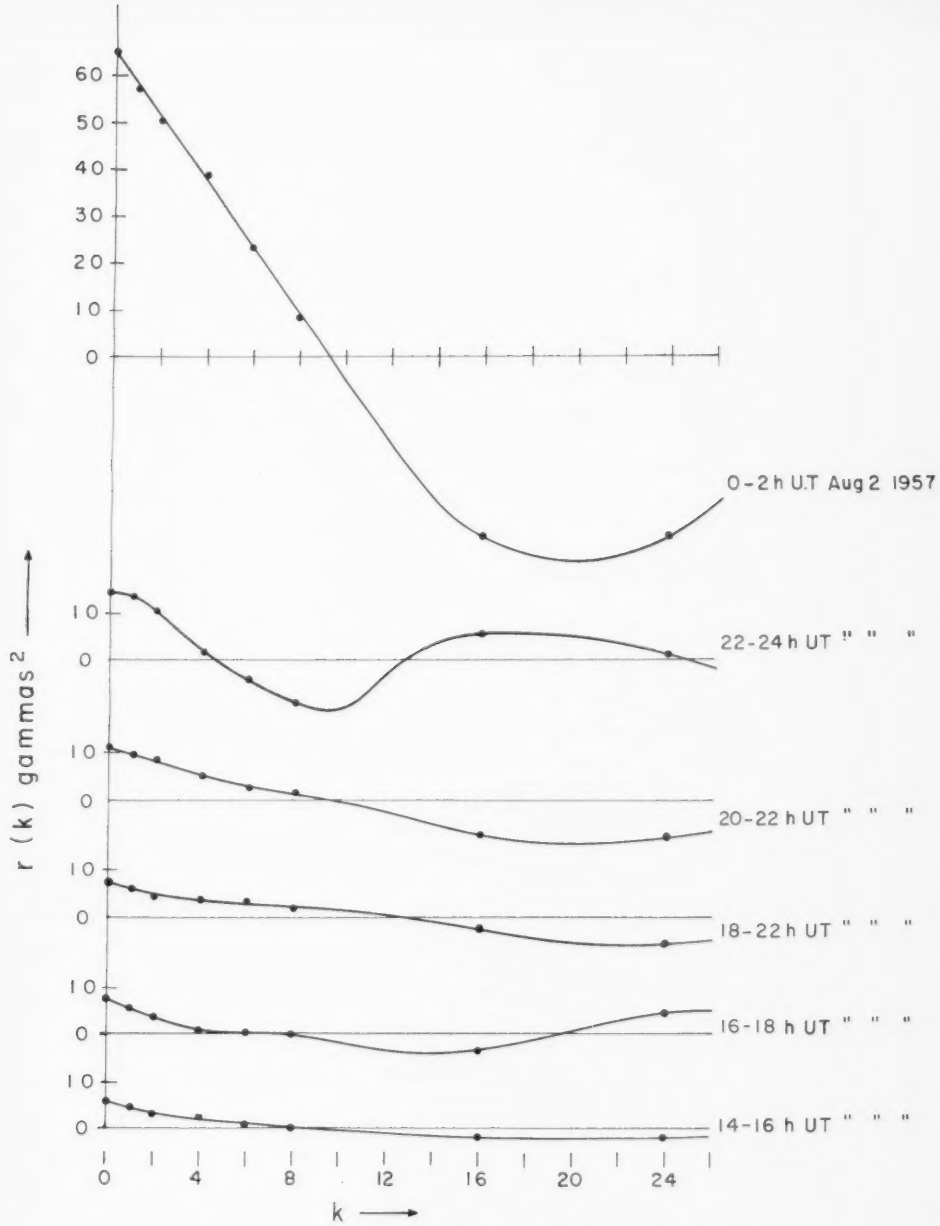

FIG. 1. Autocorrelograms for the vertical field intensity fluctuations at Meanook magnetic observatory for six day-time periods on August 2, 1957.

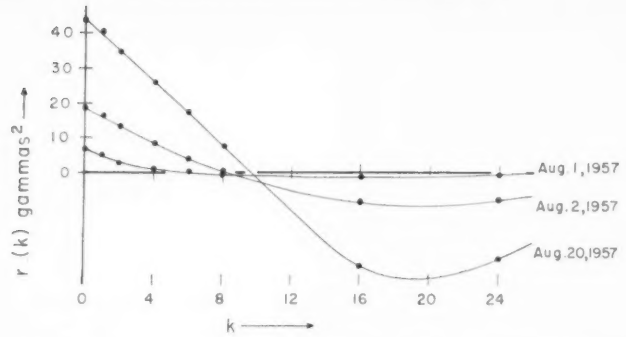

FIG. 2. The mean day-time autocorrelograms for the vertical field intensity fluctuations at Meanook magnetic observatory, August 1, August 2 and August 20, 1957.

time sets. It is clear from Table II that variations of about four-to-one in an average day can be expected at all observatories between the most disturbed and the quietest two-hourly intervals nearest local noon, and more than two-to-one between the over-all day-time averages. The ratio between the most disturbed and least disturbed two-hourly intervals nearest local midnight are in general larger than the corresponding ratio for the day-time intervals except at Resolute Bay. This is to be expected.

The mean autocorrelation function for each observatory for the day-time and night-time periods are shown in Figure 3, and are remarkably similar. In this figure the corresponding geomagnetic latitudes of the stations are indicated, together with the local time intervals in which the data have been assembled. The mean day-time autocorrelation functions were then used to calculate three parameters. Two of these parameters are shown to be the statistical errors which arise in aeromagnetic surveys because of non-linear geomagnetic time variations, when the usual survey techniques (Balsley, 1952) are employed.

The first parameter $\alpha(\tau)$ is the root-mean-square change in $Z(t)$ over the time interval τ: by definition

$$\alpha^2(\tau) = \overline{[Z(t+\tau) - Z(t)]^2} = 2[r(0) - r(\tau)]$$

and can be simply calculated once $r(\tau)$ is known. The second parameter $\beta(\tau)$ is related to the errors involved in a network of base-loops. Referring to Figure 4(a), it should be clear that when a base-line is flown first in one direction and then in another, at a time y from the turn-about point the error $\delta(y)$ produced by transient magnetic disturbance in the usual base-line adjustment to an arbitrary datum, can be written

$$\delta(y) = \frac{Z(t+y) + Z(t-y)}{2} - Z(t).$$

TABLE II. THE RATIOS $r(0)^{1/2}$ MAX.:$r(0)^{1/2}$ MIN. BETWEEN INDIVIDUAL INTERVALS IN THE THREE SELECTED DAYS, AND BETWEEN THE MEANS FOR INDIVIDUAL DAYS

Observatory	Day-time $r(0)^{1/2}$ max:$r(0)^{1/2}$ min.				Night-time $r(0)^{1/2}$ max.:$r(0)^{1/2}$ min.				Day-time	Night-time
	Aug. 1	Aug. 2	Aug. 20	Aug. 4	Aug. 1	Aug. 2	Aug. 20	Aug. 4		
Victoria	5.4	3.1	3.3		7.7	7.6	3.2		1.7	1.8
Meanook	2.1	3.4	5.3		5.8	3.5	15.4		2.4	2.7
Yellowknife	6.0	5.6	4.0		6.8	6.9	7.0		3.9	1.2
Baker Lake	5.2	2.7		3.7	5.1	11.6		3.1	2.0	1.2
Resolute Bay	6.7	2.6	5.2		3.4	4.7	2.3		1.9	2.0
Mean	5.1	3.5	4.3		5.8	6.9	6.2		2.4	1.8

This adjustment is of course perfect for linear drift or a magnetic field disturbance linearly changing with time, but as Figure 4(a) indicates, in general $\delta(y)$ does not equal zero. Averaging over all the network of baseloops is equivalent to averaging over all values of t

$$\overline{\delta^2(y)} = \overline{\left[\frac{Z(t+y) - Z(t)}{2}\right]^2} + \overline{\left[\frac{Z(t-y) - Z(t)}{2}\right]^2} + 2\cdot\overline{\frac{[Z(t+y) - Z(t)]}{2}\cdot\frac{[Z(t-y) - Z(t)]}{2}}$$

$$= \frac{3}{2}r(0) - 2r(y) + \frac{1}{2}r(2y).$$

Defining the r.m.s. error along any base line to a time τ from the turnabout point as $\beta(\tau)$ then

$$\beta^2(\tau) = \frac{1}{\tau}\int_0^\tau \overline{\delta^2(y)}dy.$$

Therefore,

$$\beta^2(\tau) = \frac{3}{2}r(0) - \frac{2}{\tau}\int_0^\tau r(y)dy + \frac{1}{2\tau}\int_0^\tau r(2y)dy$$

and can be evaluated numerically for the autocorrelation functions of Figure 3.

The third parameter corresponds to errors along a traverse line assuming adjusted values at the intersection with base lines, and linearly interpolating between the two base-line traverse intersection errors to correct the profile. This problem is an exact analogy of the study by Serson and Hannaford (1957) of the errors in large-scale magnetic charts assuming linear interpolation between scattered observations. For completeness their result is reproduced here with a different notation. Consider base lines at intervals p. The interpolated representation at a time y after the nth base-line traverse intersection is, referring to Figure 4(b),

$$(1 - y/p)Z(np) + \frac{y}{p}Z(np + p)$$

where $0 \leq y \leq p$ and n is an integer. The error is

$$Z(np + y) - (1 - y/p)Z(np) - \frac{y}{p}Z(np + p).$$

The average over all n, for a given value of y is found by squaring and averaging, giving

$$\overline{\epsilon^2(y)} = 2[1 - y/p + (y/p)^2]r(0) + 2[y/p - (y/p)^2]r(p) - 2[(1 - y/p)r(y) + \frac{y}{p}r(p - y)].$$

The mean-square error along a profile of length equivalent to a time τ, $\gamma^2(\tau)$ is obtained by averaging $\overline{\epsilon^2(y)}$ over all y from 0 to τ and putting $p = \tau$:

$$\gamma^2(\tau) = \frac{1}{\tau}\int_0^\tau \overline{\epsilon^2(y)}dy = \frac{5}{3}r(0) + \frac{1}{3}r(\tau) - \frac{4}{\tau}\int_0^\tau (1 - y/\tau)r(y)dy$$

and again can be numerically evaluated for each autocorrelation function. It should be clear that again linear effects are perfectly compensated and lead to zero error as one would expect, and that in practice these two errors interact, though in the above treatment they are considered independently.

The quantities α, β and γ were estimated from the autocorrelation curves for $\tau = 2.5\,k$ min. where $k = 0, 1, 2, 4, 6$ and 8, corresponding to the case of practical interest where traverses are usually arranged to intersect base lines every 5 to 20 minutes, and base lines are in general equal to or less than their length. Figure 5 shows the results for the day-time averages, plotting α, β and γ against $\tau^{1/2}$. It is clear that to a good approximation, in this time range, α, β and γ are proportional to $\tau^{1/2}$ and the same ratio of slopes is found at all observatories, namely 1:0.50:0.42. This linear dependence on $\tau^{1/2}$ confirms the earlier suggestion of Whitham and Loomer (1957) and the implications contained therein regarding the increase of accuracy with increased looping. Furthermore the uniform ratio of the slopes of the α and γ straight lines shows that the r.m.s. errors along traverses τ min. long is about 0.42 the r.m.s.

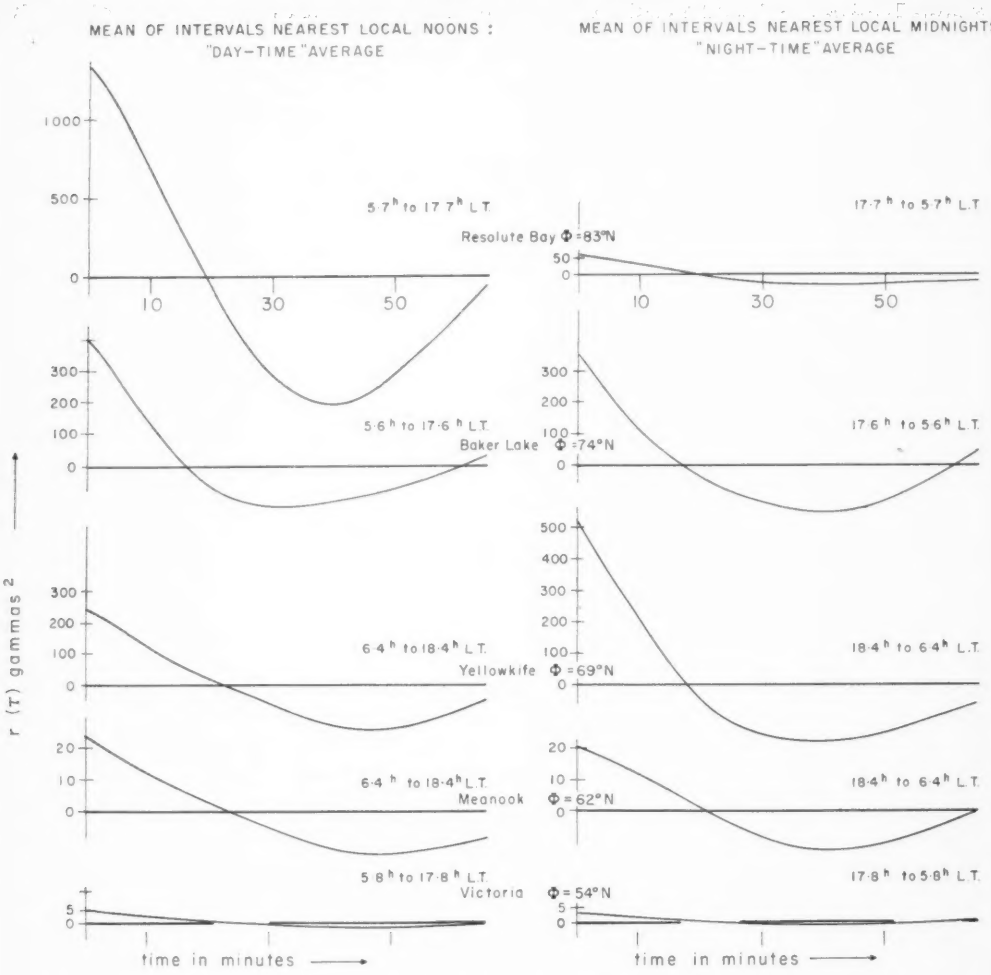
MEAN OF INTERVALS NEAREST LOCAL NOONS : "DAY-TIME" AVERAGE
MEAN OF INTERVALS NEAREST LOCAL MIDNIGHTS : "NIGHT-TIME" AVERAGE
r (τ) gammas²
5·7h to 17·7h L.T.
17·7h to 5·7h L.T.
Resolute Bay Φ=83°N
5·6h to 17·6h L.T.
17·6h to 5·6h L.T.
Baker Lake Φ=74°N
6·4h to 18·4h L.T.
18·4h to 6·4h L.T.
Yellowkife Φ=69°N
6·4h to 18·4h L.T.
18·4h to 6·4h L.T.
Meanook Φ=62°N
5·8h to 17·8h L.T.
17·8h to 5·8h L.T.
Victoria Φ=54°N
time in minutes
time in minutes

FIG. 3. The mean autocorrelation functions for the three selected days at five magnetic observatories; the data are grouped into an average of those intervals nearest to the corresponding local noons, and an average of those nearest the corresponding local midnights.

change over the interval τ, i.e. the diurnal correction between base lines. This compares favorably with the estimate of 0.5 made by Whitham and Loomer (1957) on general grounds and should, of course, be more precise. The magnitudes of α, β and γ in Figure 5 refer only to the day-time average of the three selected days, and as Table II shows, large variations between average days and even larger variations diurnally occur. Figure 6 shows the variation with latitude of β (10) and γ (10). It should be emphasized that this latitude variation is valid for this sample only, and that at other times and other seasons a maximum in β and γ between 65 degrees and 70 degrees N (the auroral zone) may occur. However it seems likely that the earlier conclusion (Whitham and Loomer, 1957) is valid, and that in general perturbations in field intensity anywhere in Canada will not exceed those at Baker Lake more than twofold.

The magnitude of the errors for a sample of average magnetic conditions is clear from Figures 5 and 6. With base-lines 10-minutes long, errors of 10 gammas in adjusted base-line values are

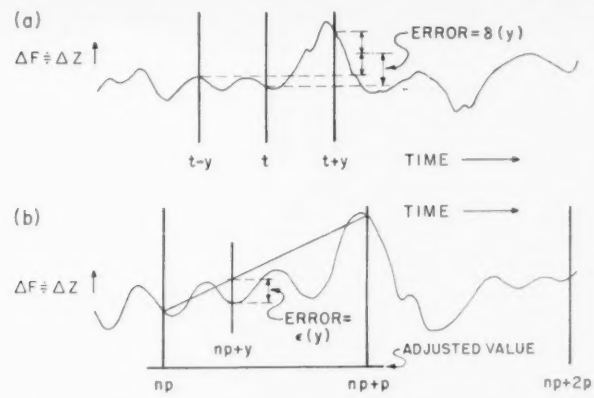

FIG. 4. (a) Linear adjustment of error along a base-loop.
FIG. 4. (b) Linear adjustment of a profile to arbitrary datum at points p apart. These diagrams are clearest if an ideal magnetic control situation is envisaged with no navigational errors and a completely uniform geology.

produced north of geomagnetic latitude 72 degrees N, and independent profile errors greater than 10 gammas north of latitude 75 degrees N. An improvement of these figures to 2.5 gammas requires in theory 4^2 or 16 times as much control. It should also be clear that in general it is preferable in a magnetic control pattern to fly base-loops some 25 percent shorter than traverse lines, and that errors of the idealized type β and γ discussed above occur substantially no matter how complicated the control pattern is made. Again if intersection differences are plotted against time and a smooth curve drawn through the points and used for correcting the profiles, the improvement in the accuracy of correction for irregular disturbance is not important. However there may be improvements in the reduction of other errors such as those caused by uncertainties in the plane's position.

An Approximate Theory

The experimentally derived straight lines of Figure 5 can be explained by the fact that for $\tau \leq 20$ minutes, the autocorrelation functions of Figure 3 can be approximately represented by $r(\tau) = A - B\tau$. Then,

$$\alpha^2(\tau) = 2[r(0) - r(\tau)] = 2B\tau$$

$$\beta^2(\tau) = \frac{3}{2}r(0) - \frac{2}{\tau}\int_0^\tau r(y)dy + \frac{1}{2\tau}\int_0^\tau r(2y)dy$$

$$= B\tau/2,$$

and

$$\gamma^2(\tau) = \frac{5}{3}r(0) + \frac{1}{3}r(\tau) - \frac{4}{\tau}\int_0^\tau (1 - y/\tau)r(y)dy$$

$$= B\tau/3.$$

Therefore α, β and γ are proportional to $\tau^{1/2}$ and their respective slopes are $(2B)^{1/2}$, $(B/2)^{1/2}$, $(B/3)^{1/2}$, the ratio being 1:0.50:0.41 in excellent agreement with the results of Figure 5. Since $r(\tau)$ becomes zero at approximately the same value of τ (20 minutes) for all observatories for this sample, $B \doteqdot r(0)/20$ gammas^2/min., and therefore α, β and γ are proportional to $r\ (0)^{1/2}$. Referring to Table II the diurnal and daily variability of α, β and γ in the sample should be clear.

The data are insufficient to define clearly the diurnal properties illustrated by Whitham and Loomer (1957). However, the gross features reported earlier can easily be seen. Thus Figure 7 illustrates the ratio of mean day-time to night-time disturbance (as defined by $r(0)^{1/2}$) as a function of geomagnetic latitude. The dominant day-time activity north of the auroral zone contrasts with the dominant night-time activity in the zone and its southern edge. At Baker Lake to the north and Victoria to the south, the day-time and night-time activities are about equal.

Figure 8 illustrates the variation with geo-

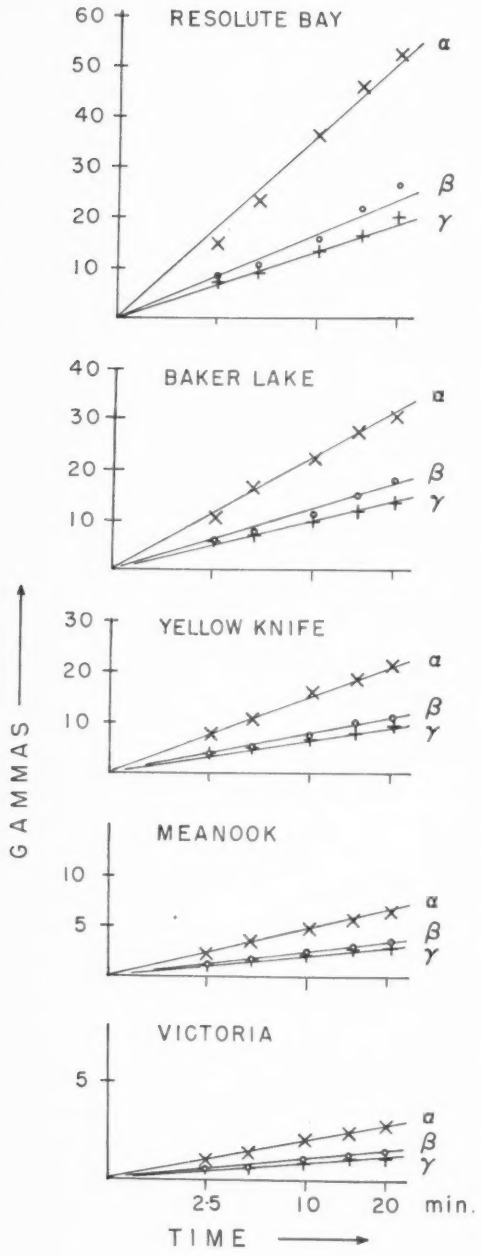

FIG. 5. Plots of the mean day-time values of $\alpha(\tau)$, $\beta(\tau)$ and $\gamma(\tau)$ against $\tau^{1/2}$ for five observatorie

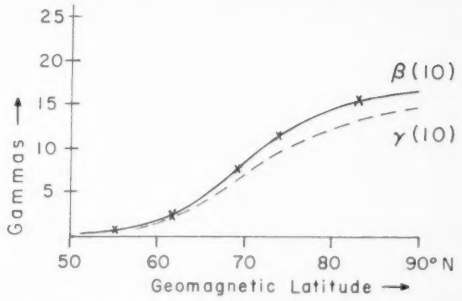

FIG. 6. The variation of $\beta(10)$ and $\gamma(10)$ for the sample with geomagnetic latitude in Canada.

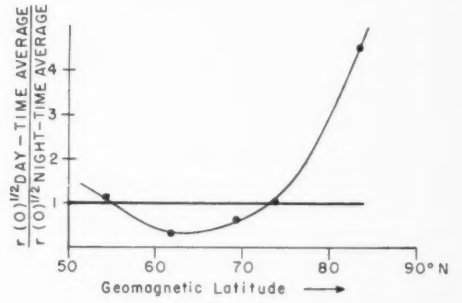

FIG. 7. Illustrating the gross features of the diurnal variation of irregular disturbance with geomagnetic latitude.

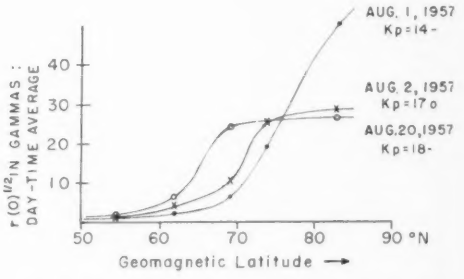

FIG. 8. The variation of the mean day-time irregular disturbance with geomagnetic latitude for the three selected days.

magnetic latitude of the day-time average $r(0)^{1/2}$ for the three selected days. On one day only does the day-time activity rise appreciably north of the auroral zone; it is rather interesting to note that the planetary index K_p appears to be weighted towards middle latitude disturbance, and may therefore be unsatisfactory for discussing high latitude disturbance.

Accuracy of the Autocorrelation Functions

The error for a finite length of series, namely 2 hrs = 48×2.5 min, for any period m×2.5 min present can be shown greater or equal to q percent where

$$q = 16m/48(1 - m/48) = 16m/48 - m).$$

For 20-minute periods, $m = 8$ and $q = 3.2$ percent only in one correlogram and is presumably some four times smaller in the day-time mean. However for 60-minute periods, the error is greater or equal to 16 percent in one correlogram.

Possible Interpretation of the Autocorrelation Functions

The problem of correlogram interpretation is very difficult and usually ambiguous (Kendall, 1955), particularly when short series of data are considered as herein. The correlogram might be considered as a series of harmonic terms (non-vanishing oscillatory correlogram) corresponding to ionospheric sources of different amplitude and frequency. The square of the amplitude of a component present of frequency f,

$$G(f) = 2\int_0^\infty r(\tau)\cos 2\pi f\tau d\tau,$$

and from the correlogram the amplitude-frequency plot can be determined.

For example for Yellowknife

$$r(\tau) = 248e^{-0.04\tau}\cos 4\tau$$

is an excellent empirical fit to the average day-time autocorrelogram for $\tau < 25$ minutes. In Figure 9 the calculated Fourier transform of this function is shown for periods less than 25 minutes. In this period range the amplitude increases approximately linearly with period and corresponds to the short period wing of a resonance at a period of 90 minutes with a resonant amplitude of 81 gamma. The physical reality of the long period resonance is doubtful and the authors believe that it is probably a consequence of the methods adopted to make the original two-hourly sets of data into stationary time series. However the decrease of amplitude with decreasing period in this frequency range may have a true physical explanation in terms of the shielding effects of the ionosphere and the induced effects inside the earth.

Another interpretation is possible. The autocorrelation functions of Figure 3 may be regarded as indicating damping and are similar to those obtained by subjecting random elements to smoothing processes. In general the series

$$u_t = \sum_{j=0}^{\infty} \omega_j \epsilon_{t-j+1}$$

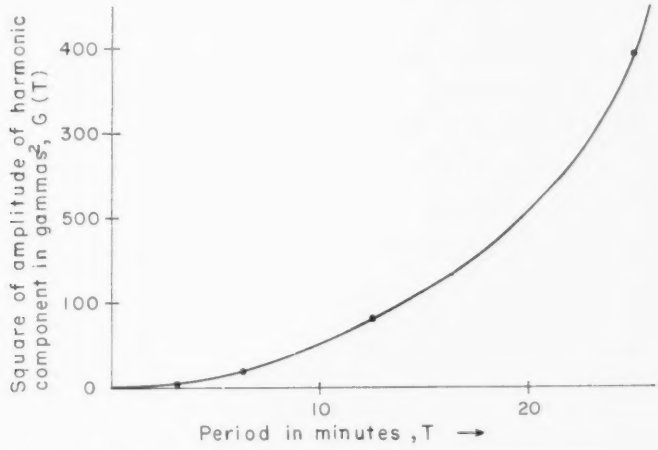

FIG. 9. The variation with period of the square of the amplitude of a periodic component for periods less than 25 minutes at Yellowknife, N.W.T.

with the weights

$$\omega_j = e^{-q(j-1)} \sin j\theta / \sin \theta$$

acting on the random elements ϵ has a correlogram $r(k)$ which can be shown equal to $e^{-qk} \sin(k\theta+\psi)/\sin\psi$ with

$$\tan \psi = (1 + e^{-2q}) \tan \theta/(1 - e^{-2q}),$$

and $q>0$ (Kendall 1955). This weighting of random elements is the equivalent of applying a filter with a response at frequency f,

$$R(f) = \int_{-\infty}^{\infty} \omega(t) e^{2\pi i f t} dt$$

which can be determined analytically in this case.

Figure 10 shows attempts to fit the mean daytime autocorrelation function at Yellowknife to this theoretical scheme. A better fit than the three curves shown is obtained for $\theta=4$ degrees, $q=0.04$ but with ψ arbitrarily put equal to 90 degrees. Since, for short series of this sort, failure to damp sufficiently rapidly can be expected, there is obviously considerable ambiguity regarding the best fitting parameters. The extreme cases $\theta=4$ degrees, $q=0.04$ and $\theta=4$ degrees, $q=0.013$ are considered below.

The weights

$$\omega_j = e^{-q(j-1)} \sin j\theta / \sin \theta$$

acting on random element ϵ_{t-j+1} can be calculated once q, θ are defined. This weighting action, or smoothing, can be regarded as produced by Yellowknife observatory rotating with the earth under a random distribution of magnetic sources in the ionosphere. The weights can be calculated for different models, and compared with the weights ω_j to distinguish which model is most reasonable. At Yellowknife (latitude=62.4 degrees N) when $k=1$ minute, the appropriate unit of distance from the rotation of the earth is $x=12.85$ km.

Consider a planar random distribution of poles at height h. A unit pole at a horizontal distance nx from Yellowknife introduces a perturbation

$$\Delta Z = h/(n^2x^2 + h^2)^{3/2}.$$

At this distance the annular area containing such poles is $2\pi nx^2 dn$ provided $n>1$. Consequently the weight ω_n applied to random poles in the annular area is

$$\omega_n \propto hnx^2/(n^2x^2 + h^2)^{3/2} \qquad \text{for } n > 1.$$

The series can be written on normalizing

$$\Delta Z \propto 1\cdot\epsilon_0 + \omega_1\cdot\epsilon_1 + \cdots \omega_n\cdot\epsilon_n + \cdots$$

with

$$\omega_n = nh^3/(n^2x^2 + h^2)^{3/2}, \qquad n \geq 1.$$

Comparison with the ideal series

$$u_t = 1\cdot\epsilon_t + e^{-q} \frac{\sin 2\theta}{\sin \theta} \epsilon_{t-1} + \cdots$$

can be done in two ways. The maximum value of ω_n occurs when $h=\sqrt{2}n_m x$ and of ω_j when

$$\tan (j_m + 1)\theta = \theta/q.$$

Equating $j_m=n_m$ determines h. For $\theta=4$ degrees, $q=0.013$, $h=340$ km. and for $\theta=4$ degrees, $q=0.04$, $h=255$ km. Alternatively the value of the maxima can be compared. Thus,

$$n_m = (3/2)^{3/2}\omega_n(\max).$$

Since for $\theta=4$ degrees, $q=0.013$, the maximum value of the series is 11.0, $n_m=20.2$ and $h=365$ km. A similar estimate for $\theta=4$ degrees, $q=0.04$ gives $h=235$ km.

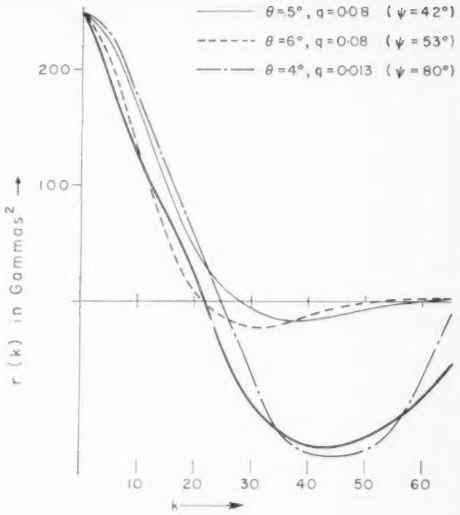

FIG. 10. Illustrating attempts to fit the mean daytime Yellowknife autocorrelation function to theoretical functions.

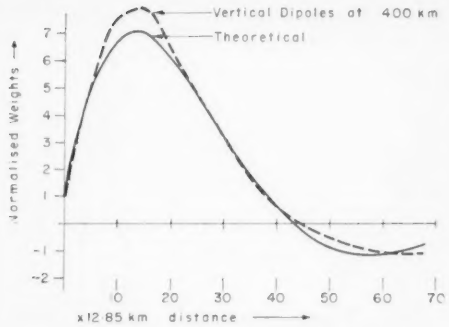

FIG. 11. The theoretical weights appropriate to values $q=0.04$, $\theta=4$ degrees and the weights appropriate to a planar distribution of vertical dipoles at 400 km.

Although these possibilities are physically reasonable, the weights in the series for ΔZ do not go negative and the fit at large distances is obviously poor. Consideration of a thin layer of dipoles removes this difficulty. Then similar arguments show that

$$\Delta Z \propto 1\cdot\epsilon_0 + \omega_1\cdot\epsilon_1 + \cdots \omega_n\epsilon_n + \cdots$$

with

$$\omega_n = n\left[h^5 - h^3n^2x^2/2\right]/(h^2+n^2x^2)^{5/2},\quad n \geq 1$$

which again can be compared with the ideal series, but now in three ways. The maximum value of ω_n occurs when $h=2.31n_mx$. Therefore, for $\theta=4$ degrees, $q=0.013$, $h=560$ km and for $\theta=4$, degrees, $q=0.04$, $h=415$ km. Similarly, equating the value of the maxima gives $n_m=1.7\omega_n(\max)$, and the values of h are 555 km and 360 km respectively. Finally the weights go negative after a value n_- given by $n_-+1=\pi/\theta$, or $n_-=44$, with $h=n_-x/2^{1/2}$. The calculated heights are 400 km for both cases.

The most constant results are given by a thin layer of vertical dipoles at a height of approximately 400 km. (corresponding to $\theta=4$ degrees, $q=0.04$). Figure 11 shows the corresponding weights plotted against the theoretical weights. The agreement is remarkably good. More complicated models such as thick layers of poles or dipoles and line current elements may also be examined by this technique, or by evaluating the autocorrelation function for specific models numerically. The results would be as ambiguous as those indicated above (see, for example, Serson and Hannaford, 1957 for calculations of the direct method) and the labor involved is not considered justified. It should, however, be noted that a thick layer of dipoles extending from 200 km through the ionospheric *F*-layers would provide as good a fit as a thin layer at 400 km, and is physically much more realistic.

Although models of this type are physically reasonable, it should be clear that since the scale length increases with co-latitude, q must increase with co-latitude to maintain the same source height. There is some evidence for this in intercomparing observatory autocorrelograms.

THE DIRECT APPROACH

Investigation of Horizontal Gradients of Geomagnetic Time Variations

In September 1959 a pair of recording proton precession magnetometers was set up near Edmonton, Alberta, in order to obtain direct comparisons of total field intensity (F) at stations less than 100 miles apart. Each instrument incorporated a standard electronic counter which measured, to the nearest 10 microseconds, the time required for 1,000 cycles of the precession signal. The digital output of the counter was changed to an analog output by a simple electronic converter so that a continuous record could be obtained on an Esterline-Angus meter from signals spaced 30 seconds apart. The full-scale sensitivity was 10^{-3} seconds, corresponding to approximately 150 gammas. Since only the fourth and fifth of the five digits registered on the counter controlled the meter deflection, the pen always remained on scale. A change in the third digit between successive readings caused the pen to travel to the opposite side of the chart. Such automatic stepping was quite unambiguous except during very large magnetic storms. The meters were clock driven, and it was necessary to check and correct the chart times regularly with radio time signals. In this way synchronization errors were held to less than 60 seconds.

One of the magnetometers was set up at Meanook Magnetic Observatory and operated continuously from August 28th to September 10th. The second one was operated 93.8 miles to the south at Calmar for a period of 65 hours from 00:00 U.T. on September 3rd to 17:30 U.T. on September 5th. It was then removed to Newbrook, 25.6 miles southeast of Meanook, and

operated for 68 hours from 00:00 U.T. on September 6th to 20:00 on September 8th. Finally, the two magnetometers were operated about 50 feet apart at Meanook for 24 hours. The locations of the three stations are shown in Figure 12. The geomagnetic latitude of Meanook is 62 degrees N. The observatory is located about 300 miles south of the center of the zone of maximum auroral frequency and geomagnetic disturbance. Overall magnetic activity in this region is very high, the hourly Z ranges usually being within a factor of two of those at the most disturbed locations in Canada.

Readings were scaled off the Esterline-Angus charts at intervals of $2\frac{1}{2}$ minutes and converted to F. In the analysis that follows time variations are represented by a sequence of values of $F_n - F_u$, where F_u is the best estimate that can be made of the undisturbed absolute intensity at a particular station and F_n is an instantaneous value of total intensity at the station. At Meanook successive $2\frac{1}{2}$ minute values of $F_n - F_u$ are designated by Θ_n and at Calmar or Newbrook by Φ_n. To study the time variations the following quantities were computed:

$$\beta = \left[\frac{1}{24}\sum_{n=1}^{24}(\Theta_n - \Phi_n)^2\right]^{1/2}$$

and

$$\sigma_h = \left[\frac{1}{24}\left\{\sum_{n=1}^{24}\Theta_n^2 - \frac{1}{24}\left(\sum_{n=1}^{24}\Theta_n\right)^2\right\}\right]^{1/2}$$

$$= \left[\frac{1}{24}(F_n - \overline{F}_n)^2\right]^{1/2}.$$

Here $\Theta_n - \Phi_n$ is the difference in the time variant part of total intensity between a pair of stations at a given time, and β is the r.m.s. difference over a given hour: σ_h is a measure of the magnetic activity for an hour, being the r.m.s. departure from the hourly mean of the total intensity at Meanook. Both quantities were computed on an I.B.M. 650 machine for every hour in which satisfactory records were obtained. Plots of β vs σ_h for the Meanook-Calmar pair and the Meanook-Newbrook pair are shown in Figure 13. Least-square straight lines through the origin have been fitted to the points.

It is clear that β increases with the level of geomagnetic activity and with the separation of the stations. The r.m.s. residual from the least squares straight line through the Meanook-Calmar data is 20 gammas, and from that through the Meanook-Newbrook data is 4 gammas. This large scatter of the individual points illustrates the complexity of the diurnal

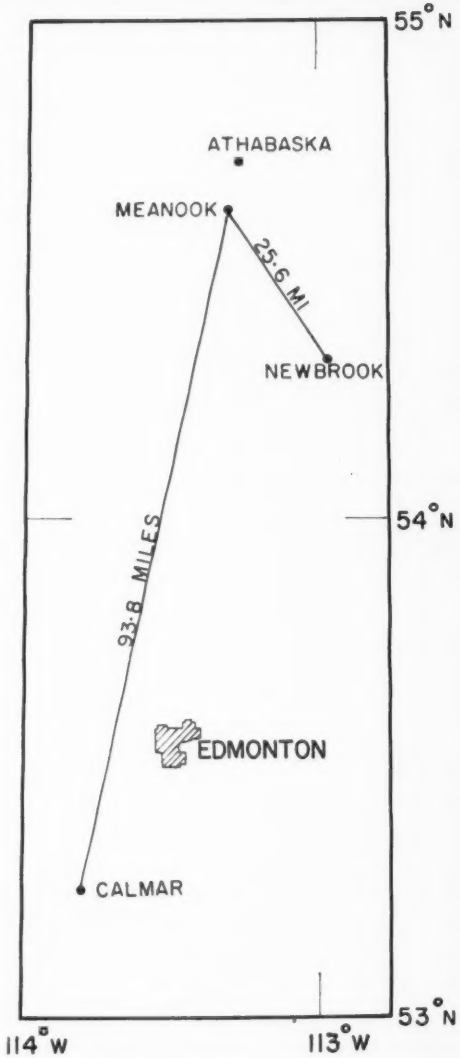

FIG. 12. The location of the two pairs of recording magnetometer stations.

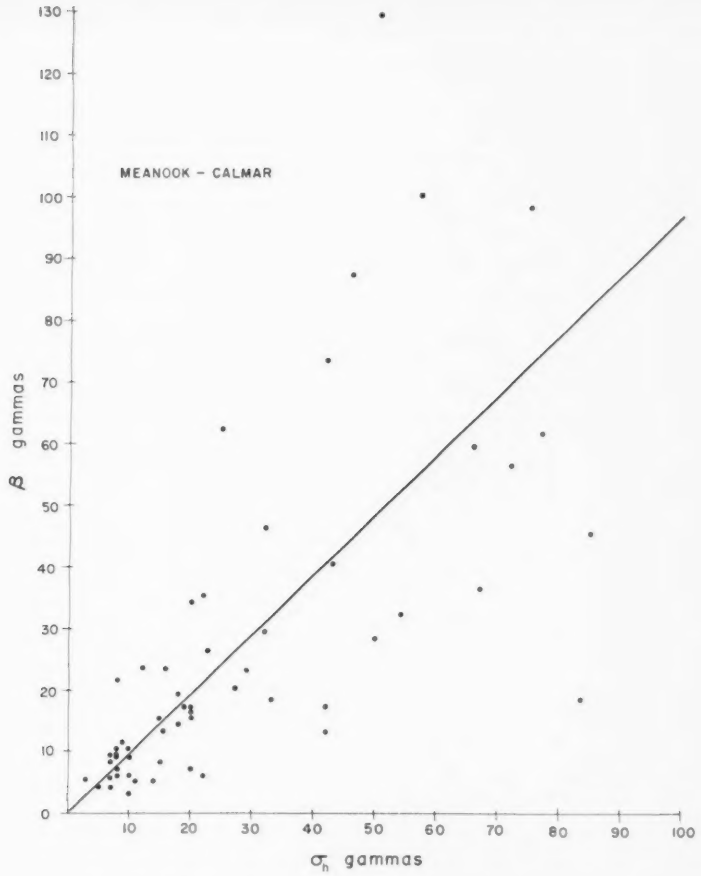

FIG. 13. (a) Plot of β against σ_h for Meanook-Calmar separation.

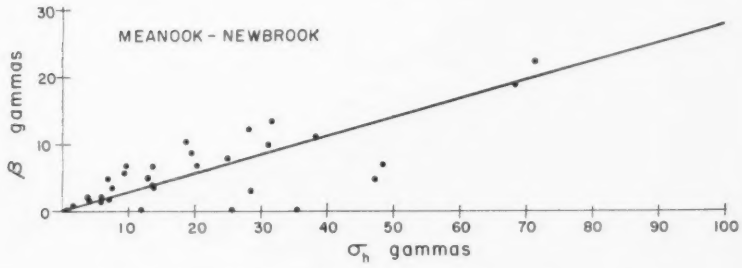

FIG. 13. (b) Plot of β against σ_h for Meanook-Newbrook separation.

problem in regions near the auroral zone. The relationship between β and σ_h can be expressed only as a statistical trend, and an accurate estimate of the level of magnetic activity at a single station will not give a reliable prediction of β except over time averages much longer than one hour.

The computed values of β depend critically on the undisturbed field value, F_u chosen for a station. Thus if the value chosen from Meanook is in error by α gammas, and for either Calmar or Newbrook by γ gammas, the true value of the r.m.s. difference over a given hour is

$$\beta' = \left[\frac{1}{24}\sum_{n=1}^{24}(\Theta_n - \Phi_n + \epsilon)^2\right]^{1/2}$$

where

$$\epsilon = \alpha - \gamma,$$

and

$$\beta'/\beta = \left[1 + \frac{2\epsilon\sum_{n=1}^{24}(\Theta_n - \Phi_n) + 24\epsilon^2}{\sum_{n=1}^{24}(\Theta_n - \Phi_n)^2}\right]^{1/2}.$$

Plots of β vs σ_h should pass through the origin. If they do not, the intercept on the β-axis is equivalent to ϵ. Figure 13 shows that whether a straight line or a more complex curve is fitted to the individual points, the β intercept will not, in either case, exceed 2 gammas. Table III shows examples of the magnitude of β'/β computed from the expression above, if ϵ is taken to be $+2$ gammas.

β'/β is within a few percent of unity only if

$$\sum_{n=1}^{24}(\Theta_n - \Phi_n)^2 \gg \sum_{n=1}^{24}(\Theta_n - \Phi_n).$$

Some of the scatter in the points plotted in Figure 13 may therefore be caused by an error ϵ of 2 gammas or less. Clearly, a good quantitative estimate of the difference in time variations of the geomagnetic field between two locations cannot be achieved unless very reliable drift-free instruments are used. Great care must be exercised in establishing F_u at the various stations.

At Meanook F_u was computed from all quiet portions of the record. The mean quiet value of F_n was determined for each hour of the day, and the mean of the 24 hourly values was taken to be F_u. The average differences in total force between Meanook and Calmar, and Meanook and Newbrook were then computed from all available quiet time data on the records to obtain F_u at the two satellite stations. Thus, if F_u at Meanook is in error by an amount α, the error γ at Calmar or Meanook should have the same sign and nearly the same magnitude. The compound error $\epsilon = \alpha - \gamma$ is minimized with this procedure.

TABLE III. THE RATIO OF r.m.s. TIME VARIATION DIFFERENCES ASSUMING AN ERROR OF 2 GAMMAS IN THE DIFFERENCE IN THE UNDISTURBED FIELDS AT TWO LOCATIONS

Date	Hour (U.T.)	$\sum_{n=1}^{24}(\Theta_n - \Phi_n)$	$\sum_{n=1}^{24}(\Theta_n - \Phi_n)^2$	β'/β
		gammas	gammas^2	
Sept. 3	00–01	280	3,910	1.14
3	10–11	6,050	19,700	1.49
4	01–02	−1,720	22,800	0.84
5	00–01	224	9,040	1.05
6	02–03	89	3,480	1.06
6	06–07	−13	11,800	1.00

To investigate the statistical dependence of the difference in total force between a pair of stations on the level of magnetic activity, r.m.s. values of $(\Theta_n - \Phi_n)$ were computed over times of approximately 10 hours. To do this individual hours were grouped together according to their value of σ_h. Thus, for the Meanook-Calmar pair all hours having σ_h in the range 0–8 gammas were placed in one group, all hours with σ_h in the range 9–16 gammas in another group, and so on. For each group the quantities

$$B = \left[\frac{1}{N}\sum_{n=1}^{N}(\Theta_n - \Phi_n)^2\right]^{1/2}$$

and

$$\bar{\sigma} = \left[\frac{1}{H}\sum_{n=1}^{H}\sigma_h{}^2\right]^{1/2}$$

were calculated. H is the total number of hours in a group and $\bar{\sigma}$ is the r.m.s. value of σ_h for the group. N is the total number of $2\frac{1}{2}$ minute values within the group, and B is the r.m.s. difference in total intensity over the time $2\frac{1}{2}$ N minutes. The results are tabulated below in Table IV. N is not usually equivalent to 24 H because short portions

TABLE IV. THE DEPENDENCE OF B AND $\bar{\sigma}$ ON THE r.m.s. DISTURBANCE IN EACH HOUR, σ_h.

Range of σ_h gammas	H	N	$\bar{\sigma}$ gammas	B gammas
	I—Meanook—Calmar			
0–8	12	271	7.2	8.6
9–16	12	287	12.5	12.6
17–23	11	253	20.2	25.1
24–43	10	240	35.3	39.3
>43	12	277	66.5	69.2
	II—Meanook—Newbrook			
0–10	10	229	6.5	3.2
10–26	10	240	18.0	6.4
>26	10	234	45.3	12.2

of some of the records were lost due to temporary power failures, excessive magnetic disturbance, or electrical noise picked up by the magnetometer coils. For some hours, therefore, less than 24 values were available.

B is plotted against $\bar{\sigma}$ in Figure 14. The equations of the least-squares straight lines, not forced through the origin are:

$$\text{Meanook-Calmar} \qquad B = 1.89 + 1.19\bar{\sigma}$$

$$\text{Meanook-Newbrook} \qquad B = 1.94 + 0.23\bar{\sigma}.$$

If the assumed linear relationship between B and $\bar{\sigma}$ were strictly valid, the positive intercepts of these lines would be equivalent to ϵ, and corrected values of B could be computed. However, the points could undoubtedly be fitted by smooth curves having negligible intercepts, so that it is difficult to tell how much the intercepts computed above depend on a true error ϵ, and how much they depend on forcing the linear relationship. Nevertheless, it is clear that ϵ is smaller than 2 gammas, and consequently none of the computed values of B can be in error by more than 10 percent. Least-squares straight lines through the origin have been adopted. Their equations are

$$\text{Meanook-Calmar} \qquad B = 1.07\bar{\sigma}$$

$$\text{Meanook-Newbrook} \qquad B = 0.29\bar{\sigma},$$

the standard errors of the slopes being 0.03 in both cases. The r.m.s. residuals are 2.0 gammas and 1.1 gammas respectively.

It s concluded that over a long time averages the r.m.s. difference in the variations of total intensity between a pair of stations is directly proportional to the activity $\bar{\sigma}$ in the range from zero to 50 gammas. Furthermore, the ratio of the

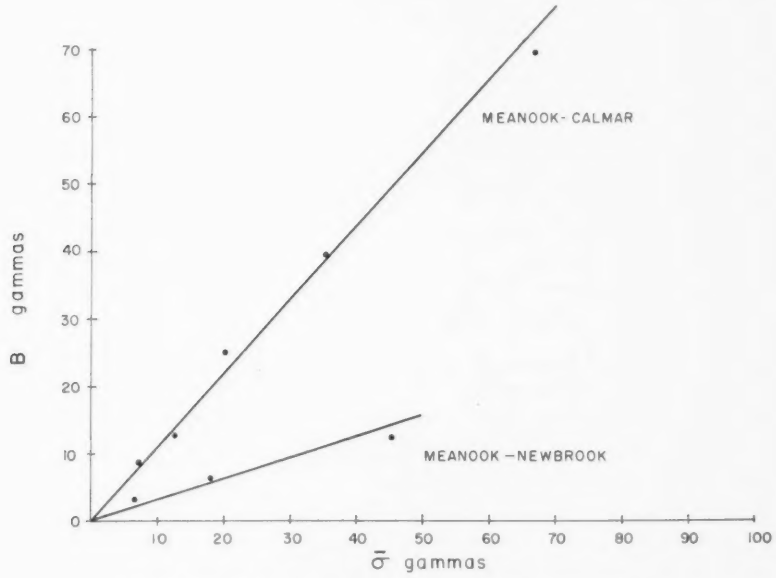

FIG. 14. Plots of B against $\bar{\sigma}$ with least-squares lines through origin.

slopes of the straight lines is 3.7, and the ratio of the separation of the pairs of stations is 3.7. This suggests that, in this region, B is roughly proportional to the separation of the stations in the range zero to 100 miles, i.e. $B \doteqdot \kappa \bar{\sigma} d$ where d is the separation in miles and κ is a constant. The average value of κ for the two pairs of stations is 0.011 gammas per unit r.m.s. level of hourly activity per mile.

The following points must be emphasized:

(1) This result is only valid when long time averages ($\sim$10 hrs) are considered.

(2) Records from more than two pairs of stations are required to substantiate that $B/\bar{\sigma}d$ is really constant over the range of 100 miles. At greater separations B will probably approach a saturation value. The azimuth of the line of stations may also be important.

(3) Disturbances with periods shorter than a few minutes are largely ignored in this treatment; more research is necessary to establish that the same statistical proportionality is valid for shorter period disturbance.

Application to Aeromagnetic Surveys

The relation $B \doteqdot \kappa \bar{\sigma} d$ provides a ready method of estimating the size of error to be expected if a single ground control station is used to correct for time variations during an airborne magnetometer survey within a radius of 100 miles. For example, at a distance of 50 miles from Meanook at a time when the hourly r.m.s. activity is 10 gammas, the predicted r.m.s. error (B) is 5.5 gammas. Alternatively the relation can be used quantitatively for indicating when magnetic conditions are sufficiently quiet for a flight to be undertaken. However, the scatter of the points in Figure 13 clearly demonstrates the large uncertainties attached to such predictions for individual hours. It should be stressed that the value of κ estimated here applies only to the Meanook-Edmonton region. In other areas and at other seasons a simple linear relationship may not be valid. The models discussed earlier which appear capable of explaining the shape of the autocorrelation functions of magnetic disturbance suggest that for east-west separation of stations $B(d)$ is analogous to $\alpha(\tau)$ and hence $B(d) \propto d^{1/2}$ over distances less than 100 miles. Much more experimental work is required to establish that B depends on $\bar{\sigma}$ and d in a truly consistent manner.

Before it is possible to judge if the empirical relationship can be usefully applied, it is necessary to estimate the percentage of time for which geomagnetic disturbances are small enough for airborne surveys, with the direct correction approach, to be undertaken. To do this, the number of hours in September 1959 for which the r.m.s. error B lies within a certain range have been estimated. The results are displayed in the histograms of Figure 15. Between Meanook and Calmar B was less than 10 gammas for 44 percent of the total number of hours (720) in the month, while between Meanook and Newbrook B was less than 5 gammas for 69 percent of the month. Since the proton precession magnetometers were not operated throughout all of September, these histograms were derived by an indirect approach. The hourly Z ranges were measured from the Meanook LaCour magnetograms for the whole month, and the Z ranges plotted against $\bar{\sigma}_h$ for 102 hours during which proton precession records were available. The least-squares straight line through the origin is $Z_{\text{range}} = 3.36\ \sigma_h$, the standard error of the slope being 0.09. A value of B was derived for each of the 720 hourly ranges by means of this relation and the earlier relations between B and $\bar{\sigma}$.

The average value of the index A_p for September 1959 was 28, indicating that the geomagnetic disturbance level for the month was rather high, about 40 percent higher than the average for the two years 1958 and 1959. Thus, the frequency distributions of B over a longer time (say, a year) would probably contain higher percentages in the lower ranges. The above results refer to all hours of the day; the day and night-time differences are illustrated in the first part of the paper.

It might be remarked that in a practical application of a direct correction, errors of the type ϵ are unimportant since the datum of an aeromagnetic chart is arbitrary.

A COMPARISON OF THE DIRECT AND INDIRECT APPROACHES

Both the approaches investigated in this paper provide quantitative estimates of the errors associated with two distinct survey techniques for hypothetical cases and at particular times. A

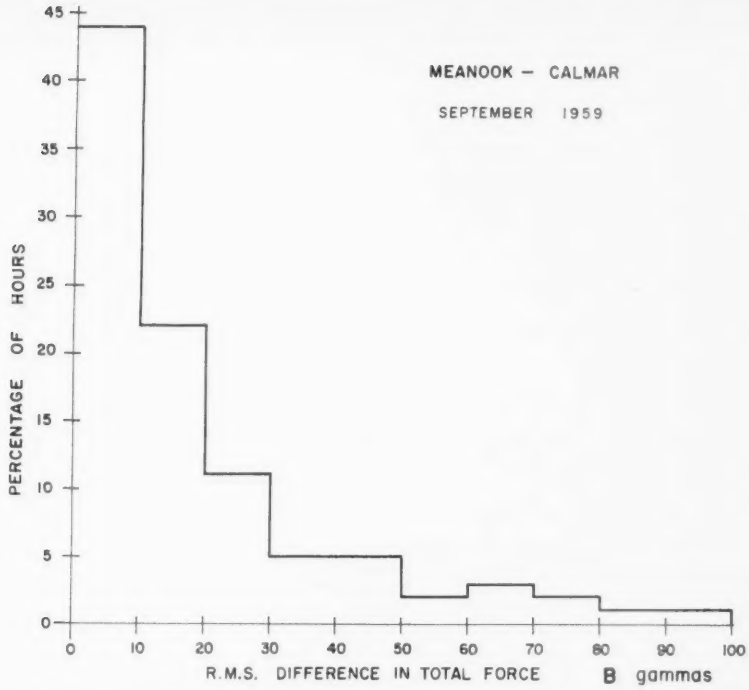

FIG. 15. (a) Histogram of percentage of hours in September 1959 with r.m.s. difference in total field intensity between Meanook and Calmar.

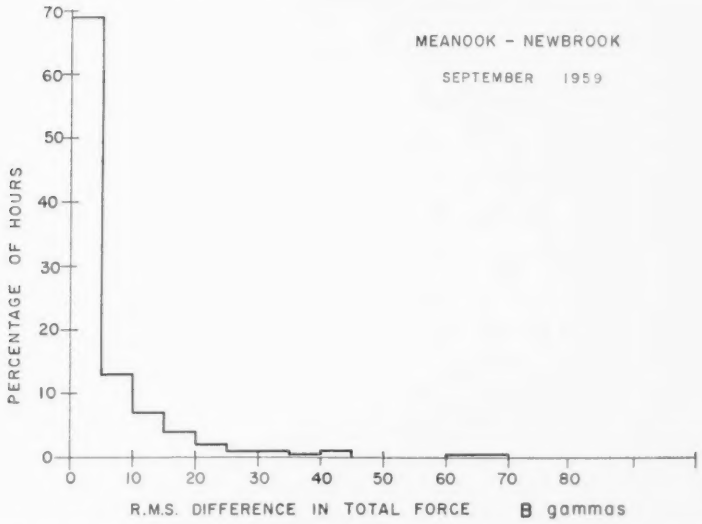

FIG. 15. (b) Histogram of percentage of hours in September 1959 with r.m.s. difference in total field intensity between Meanook and Newbrook.

rigorous comparison of the two methods is not possible, but an approximate one can be made in the Edmonton-Meanook area using the formulae outlined earlier together with other simplifying assumptions regarding the data samples used. Thus with 2.5 minute looping (say, 6 miles) in this region, the results of Figure 5 indicate overall errors in the indirect approach of $(\beta^2+\gamma^2)^{1/2} \doteqdot 1.6$ gammas during the day-time hours of three days, for which $\bar{A}_p=8.3$. When $\bar{A}_p=28$, a reasonable estimate of the overall r.m.s. error is 5 gammas. This becomes equal to the r.m.s. error for approximately 70 percent of all hours if direct corrections were made from a station 26 miles distant, assuming, of course, the time synchronization is perfect. Corrections from a ground station 50 miles away would be two times more uncertain in this region: the same result is obtained with 24-mile spacing using the indirect method.

It must be emphasized that the problem of the time synchronization of records, data-handling problems in obtaining intensity data in a reciprocal form in certain techniques, and considerations of the costs and logistics of different techniques have necessarily been ignored. Such considerations may strongly influence the practical application of the theoretical results above. For example, with many large surveys the density of ground stations required for a given accuracy may be impractical. Again extrapolation of these conclusions to other regions and conditions of disturbance may not be valid.

FUTURE WORK

Much work remains to be done in different geographical locations on the change of coherency of irregular magnetic disturbance with increasing separation and increasing disturbance. Station pairs along north-south and east-west lines should be occupied to test the ideas given above. It is clear to us that unless the data obtained are handled digitally, no more than qualitative conclusions can be reached. We therefore plan using recording proton precession magnetometers with tape-punch output (suitable for machine processing), an analog recording device for monitoring purposes and automatic time control from a suitable secondary time standard. This should remove the manual steps and some of the uncertainties in the work described above.

With the data available directly in digital form the spatial coherency of disturbance as a function of the period of the disturbance can be examined. At the short period end (10- to 100-second periods) comparitively local geological effects, the influence of the sea, etc., may be found: at the long period end (12, 24-hour periods) the coherency would be expected to remain high for greater distances.

It is clear that the validity of the survey procedures discussed above requires further experimental and theoretical investigation.

ACKNOWLEDGMENTS

We wish to thank Paul H. Serson for his advice on the design and construction of the recording proton precession magnetometers used, and Professors Garland and Vozoff of the University of Alberta for permission to use the Calmar site and assistance at Calmar during the experimental work. The assistance of Miss Anne B. Cook and the staff at Meanook Magnetic Observatory in the experimental program is gratefully acknowledged.

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GEOPHYSICS, VOL. XXVI, NO. 2 (APRIL, 1961), PP. 229–241, 7 FIGS.

A SIMPLE INTEGRAL TRANSFORM AND ITS APPLICATIONS TO SOME PROBLEMS IN GEOPHYSICAL INTERPRETATION*

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Abstract: A simple integral transform, defined by

$$f(x) = \int_{-\infty}^{+\infty} F(x, y)dy,$$

where $F(x, y)$ represents the measured geophysical field and x and y are suitably chosen directions, has been used for formulating convenient interpretation techniques to some geophysical problems that are normally not amenable to easy quantitative interpretation. Some synthetic numerical examples are given.

INTRODUCTION

It is well known that the application of integral transforms of the form

$$f(x, p) = \int_{a}^{b} F(x, y)K(y, p)dy$$

to the solution of a problem reduces the number of variables by one. Here $F(x, y)$ is the function to be transformed, $K(y, p)$ is the kernel of the transform and p is an integral variable assuming values 1, 2, 3, · · · . More specifically, by the use of integral transforms, a three-dimensional problem can be reduced to a series of two-dimensional problems and a two-dimensional problem can be broken up into a series in one dimension. The results of the reduced series are then suitably combined to give an inverse transformation, which is the answer to the original problem.

While the above outline appears simple enough, practical difficulties arise. First, the numerical evaluation of the integral is often time-consuming because the value of the weighting function or the kernel $K(p, y)$ is different for different values of y. Second, it is necessary to find the transform separately for quite a few integral values of p starting from unity, the actual number depending on the rate of convergence. Third, the solution to the original problem has to be recovered by taking an inverse transform, a process which is not without labor. This recovery is only possible because the missing variable y remains dormant in the parameter p. The reduction of a dimension is only apparent and partial, because the continuous variable y is merely replaced by a discrete variable p. The long numerical processes tend to annul the advantage of using the integral transforms in many of the problems.

In this paper, a much simpler transform of the type

$$f(x) = \int_{-\infty}^{+\infty} F(x, y)dy \qquad (1a)$$

or

$$f(y) = \int_{-\infty}^{+\infty} F(x, y)dx \qquad (1b)$$

will be examined. It is clear that the numerical evaluation of such an integral will be very easy because (1) the kernel is simply unity and is invariant with the x or y co-ordinate and (2) the integral parameter p is absent. For the latter reason, however, a unique inverse of (1a) or (1b) cannot be taken. This is a blessing in disguise because the labor involved in the operation of finding the inverse is altogether eliminated, provided, of course, one makes certain that the character-

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istic properties that are to be determined from the solution of the original problem are not altered by the application of (1a) or (1b). For actual computational work, (1a) and (1b) can be approximated as closely as one pleases by the following sums:

$$f(x) = \Delta y \sum^{n} F(x, y_n) \tag{2a}$$

$$f(y) = \Delta x \sum^{n} F(x_n, y). \tag{2b}$$

In this work, $F(x, y)$ will be identified with the various types of geophysical anomalies observed on the ground surface. It will be found that the application of this transform will provide us with methods of interpretation in many cases in which simple interpretation rules are not otherwise available or derivable.

FINITE LINE SEGMENT

Gravity or Vertical Magnetic Anomaly

The vertical field at any point (x, y) due to a line of ordinary or magnetized (monopolar) matter having a length $2l$ and an orientation along the y direction is

$$F(x, y) \equiv g(x, y) = \frac{\gamma m h}{x^2 + h^2}\left[\frac{l - y}{\sqrt{x^2 + h^2 + (y - l)^2}} + \frac{l + y}{\sqrt{x^2 + h^2 + (y + l)^2}}\right], \tag{3}$$

where γ is the gravitational constant, m is the mass (or pole) per unit length and h is its depth below the ground surface (x, y, o). On integrating (3) along the y direction according to (1a), one gets

$$f(x) = \frac{2\gamma(2ml)h}{x^2 + h^2}, \tag{4}$$

which is nothing but the anomaly field of an infinitely long line mass at the same depth h and oriented along y. The depth is given by $h = x_{1/2}$, where $x_{1/2}$, as usual, is the distance from the maximum point to that at which the anomaly falls to half the maximum value.

If, on the other hand, the expression (3) is integrated along the x direction according to (1b), one obtains

$$f(y) = 2\gamma m[\arctan\{(l + y)/h\} - \arctan\{(y - l)/h\}] = 2\gamma m\theta, \tag{5}$$

θ being the angle subtended by the line segment at any point on the y-axis. Relation (5) expresses the gravity anomaly due to an infinitely long strip of depth h, width $2l$, mass per unit area m and orientation along x direction. The values of both h and $2l$ can be easily determined by a simple geometrical construction Egyed (1948) and Jung (1953).

A numerical example of interpretation by this method is shown in Figure 1. The predicted values of h and $2l$ are 1.01 and 2.07 units respectively, and check excellently with the theoretically assumed values. Figure 1(a) also shows the simple template used for the computation with $\Delta x = \Delta y = 0.2$ unit. All one has to do is to hold the transparent template parallel to the axis of integration at various positions along the orthogonal axis, sum the field values at each division on the template on a calculating machine and multiply the sum by 0.20. The total time taken in this particular example in evaluating the two integrations along x and y directions and the interpretations shown in Figures 1(b) and 1(c) was only three hours. It is obvious that the value of the remaining unknown, that is, m, can also be determined easily enough.

Horizontal Magnetic Anomaly

If X and Y are the two components of the horizontal force caused by the same line segment, then it is found that

$$\int_{-\infty}^{\infty} X dy = \frac{2(2ml)x}{x^2 + h^2} \quad \& \quad \int_{-\infty}^{\infty} Y dy = 0. \tag{6}$$

This is of course the horizontal anomaly of an infinitely long line pole, whose depth is simply equal to $\frac{1}{2}|x_{\max} - x_{\min}|$ of the integrated profile. Integration with respect to the x axis, on the other hand, gives

$$\int_{-\infty}^{\infty} X dx = 0 \quad \& \int_{-\infty}^{\infty} Y dx = 2m \ln (r_1/r_2), \tag{7}$$

where r_1 and r_2 are the distances of a profile point from the two ends of the line segment. The right-hand sides of the equations in (7) express the horizontal anomaly of an infinite strip of width $2l$

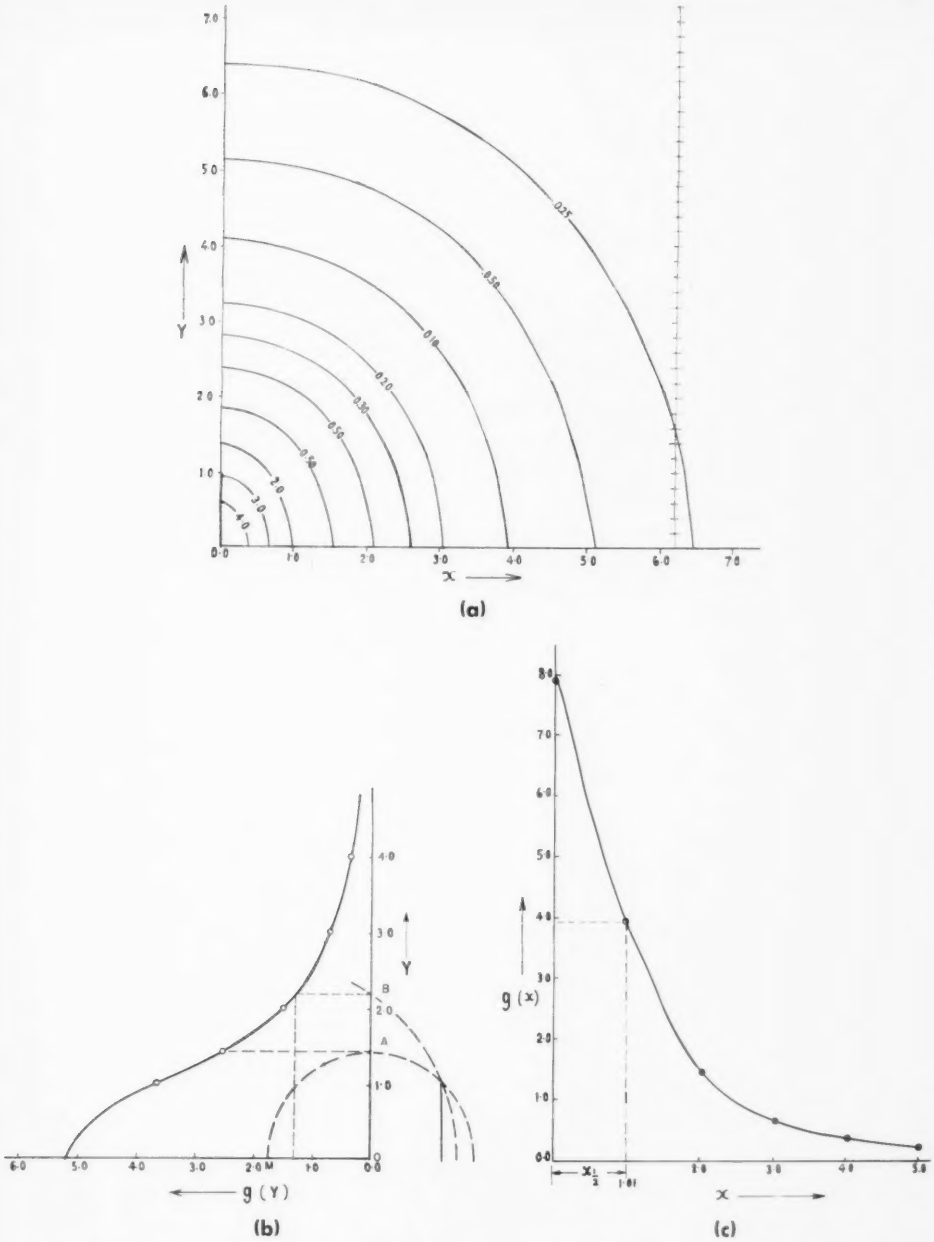


FIG. 1. (a) Gravity anomaly contours (milligals) caused by a line segment 2 units long, 1 unit in depth and mass per unit length 5×10^{4} gms. (b) Profile after integration along x direction, that is, across strike. Dashed lines and arcs show Egyed's construction. With center O and radius $OA=x_{1/2}$, draw a circle. An arc with center M and radius MB ($OB=x_{1/4}$) cuts this circle at two points. A straight line joining the two points of intersection defines the line segment. (c) Profile after integration along strike and its interpretation.

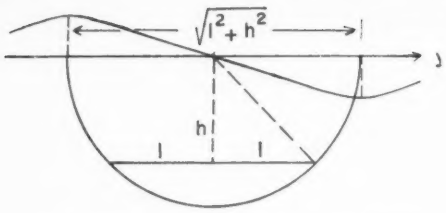


FIG. 2. Geometrical location of finite line segment from horizontal magnetic anomaly.

and oriented along the x direction. The distance between the two extrema on this integrated profile is, therefore, $2(l^2+h^2)^{1/2}$. The line segment will thus be a horizontal chord of the semi-circle with center exactly midway between the extrema and radius $\frac{1}{2}|y_{max}-y_{min}|$. Since h is already known, the chord can be uniquely located (Figure 2).

Total Intensity (Aeromagnetic) Anomaly

Henderson & Zietz (1948) gave methods for the interpretation of total intensity anomaly maps for point and infinite line sources. In low latitudes where both the positive and the negative centers are easily discernible, the methods admit of considerable simplification. For a point pole at a depth h and a profile in the magnetic meridian through the positive and the negative centers, the depth is given by

$$h = \frac{2(\text{distance between } +ve \text{ and } -ve \text{ centers})}{\sqrt{8+9\tan^2 I}}, \tag{8}$$

I being the known inclination of the terrestrial field. The lateral position is obtained (in northern latitudes) by measuring a distance of

$$\frac{1}{2}\left[\frac{3\tan I}{\sqrt{8+9\tan^2 I}} \mp 1\right] \times (\text{distance between } +ve \text{ \& } -ve \text{ centers}) \tag{9}$$

northwards from the positive center (use minus sign) or southwards from the negative center (use plus sign). The corresponding expressions for an infinite line source are

$$h = \frac{\cot I \sin\beta}{2\sqrt{1+\cot^2 I \sin^2\beta}} \times (\text{shortest distance between two extrema}) \tag{10}$$

and

$$\frac{1}{2}\left[\frac{1}{\sqrt{1+\cot^2 I \sin^2\beta}} \mp 1\right] \times (\text{shortest distance between two extrema}), \tag{11}$$

where β is the acute angle between the line source and the magnetic north.

For a line pole of finite length $2l$, depth h and orientation as shown in Figure 3, the aeromagnetic anomaly is

$$T(x,y) = m\cos I\cos\beta\left(\frac{1}{r_1}-\frac{1}{r_2}\right) + \frac{m(y\cos I\sin\beta - h\sin I)}{y^2+h^2}\cdot\left\{\frac{l-x}{r_1}+\frac{l+x}{r_2}\right\}, \tag{12}$$

with $r_1=[(x-l)^2+y^2+h^2]^{1/2}$ and $r_2=[(x+l)^2+y^2+h^2]^{1/2}$. We then have

$$\int_{-\infty}^{\infty} T(x,y)dx = \frac{2(2ml)(y\cos I\sin\beta - h\sin I)}{y^2+h^2}, \tag{13}$$

an expression that describes the aeromagnetic anomaly of an infinitely long line pole parallel to the x axis and having a pole strength of $2ml$ per unit length. This integrated profile may, therefore, be interpreted for depth and location (on plan) by formulae (10) and (11), or the methods evolved by Henderson & Zietz and Smellie, depending on the latitude of the place. Now let us subtitute $x=x'\sin\beta+y'\cos\beta$ and $y=y'\sin\beta - x'\cos\beta$ in expression (12), so that the coordinate axes x and y rotate counterclockwise by an angle $(90-\beta)$ and assume the new positions x' and y'. It is found that

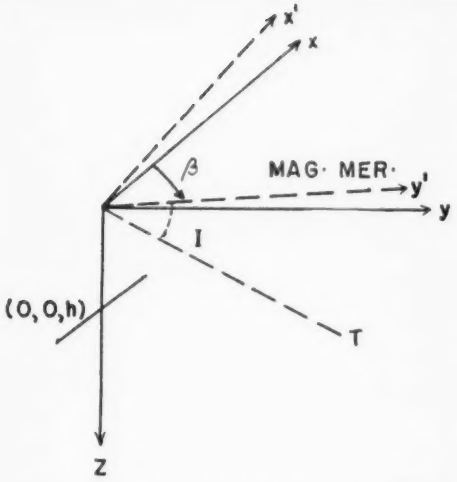


FIG. 3. Relationship of the finite line segment to the two systems of co-ordinate axes. The plane $z=0$ corresponds to flight level. T is direction of terrestrial magnetic field.

$$\int_{-\infty}^{\infty} T(x', y')dy' = 2\{m \sin I(\sin\beta + 2l\cos\beta)\} \cdot [\arctan\{(x' + l\sin\beta)/h\} - \arctan\{(x' - l\sin\beta)/h\}]. \quad (14)$$

In words, if the total intensity anomaly map is integrated in the direction of the magnetic meridian, it results in a profile that may be considered as being simply *the vertical magnetic anomaly* resulting from a uniform strip of apparent width $2l \sin\beta$, depth h and mass per unit area $m \sin I(\sin\beta + 2l\cos\beta)$, and with an orientation along the meridian. Its position can be determined by Egyed-Jung's geometrical construction. In addition to determining the remaining unknown $2l$, it also provides a check on the previous depth estimate. In some cases, the strike direction may not be known with any degree of certainty because the line segment happens to be short. Under such circumstances, it may be more convenient to carry out the integration at right angles to the magnetic meridian according to the expression

$$\int_{-\infty}^{\infty} T(x', y')dx'$$

instead of the one indicated in (13). It can be shown that the resultant profile will be the same as the *total intensity anomaly* caused by a uniform strip of apparent width $2l\cos\beta$, depth h and orientation along magnetic east-west. The apparent width can then be computed from

$$2l\cos\beta = [(y'_{\max} - y'_{\min})^2 - 4h^2\sec^2 I]^{1/2}, \quad (15)$$

since h is already known. The center of the strip lies a distance

$$|h\tan I - (h^2\sec^2 I + l^2\cos^2\beta)^{1/2}|$$

northwards from the maximum or a distance

$$[h\tan I + (h^2\sec^2 I + l^2\cos^2\beta)^{1/2}]$$

southwards from the minimum. The length of the line segment is the square root of the sum of the squares of the two apparent widths and its location on plan will be given by a diagonal of the rectangle formed by the intersection of the two infinite strips. If the maximum or the minimum is not well developed, so that relation (15) is not usable, one can determine $2l\cos\beta$ approximately from Figure 4 by measuring the distance between the two half-maximum points on the $\int_{-\infty}^{\infty} T(x', y')dx'$ profile.

Finite Line Segment of Dipoles: Consider a finite line of magnetic dipoles (Figure 3) striking at an acute angle β with the magnetic north. An integration of its anomaly along the strike will virtually replace the finite segment by an infinite one at the same depth and with the same orientation. Its lateral position and depth can be found by Smellie's method, while the length $2l$ remains undetermined. A second integration along the magnetic meridian will yield a symmetrical profile of the *vertical magnetic anomaly* resulting from an infinitely long vertically polarized strip of width $2l\sin\beta$, depth h and orientation along magnetic northsouth. If $x_{1/2}'$ and x_0' are respectively the distances from the maximum point to those at which the (integrated) anomaly falls to half the maximum value and to zero, then the depth and the width are given by

$$\left.\begin{aligned} h &= [x_0'^2 - \{(x_{1/2}'^4 + 3x_0'^4)/(4x_{1/2}'^2)\}]^{1/2} \\ l\sin\beta &= [x_{1/2}'^4 + 3x_0'^4]^{1/2}/(2x_{1/2}') \end{aligned}\right\}. \quad (16)$$

In case an integration at right angles to the magnetic meridian is necessary, $2l \cos\beta$ can be roughly determined from Figure 5 by measuring, as before, the distance between the two half-maximum points.

RECTANGULAR LAMINA

Whenever the gravity or the vertical magnetic anomaly (circular or elliptical) is too wide to be explained by a point source or a finite line segment at geologically possible depths, the assumption of a square or a rectangular lamina will offer a more satisfactory depth estimate. In particular, the approximation is useful in faulted regions of low dip, symmetrical anticlines or synclines and vertically polarized basement or dykes—when these are of limited lateral extent.

The four unknowns, depth, length, width and mass per unit area cannot ordinarily be determined except by the long procedure of fitting the observed anomaly by trial and error. The application of the simple integral transform (1a) and (1b), however, radically simplifies the interpretation problem.

It is obvious that two separate integrations, one along the length and the other along the breadth, will result in two mutually orthogonal profiles characteristic of infinite strips. These can

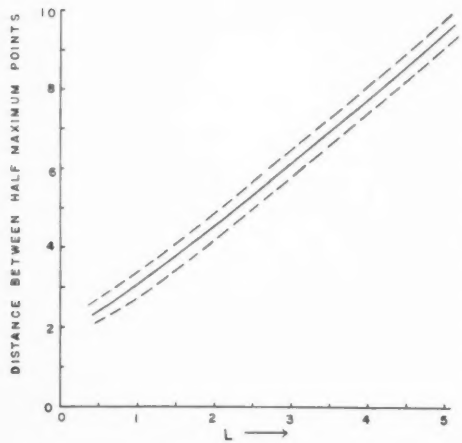


FIG. 4. Dependence of distance between half-maximum points on the apparent width $2L(\equiv 2l \cos\beta)$ for total intensity profiles caused by infinitely long strips oriented at right angles to magnetic meridian. All distances in units of depth (which is already known). Use solid curve. Dashed lines are limits of variation caused by changes in inclination I.

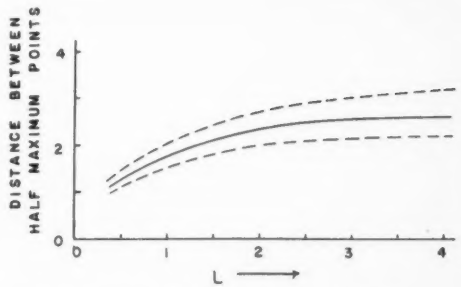
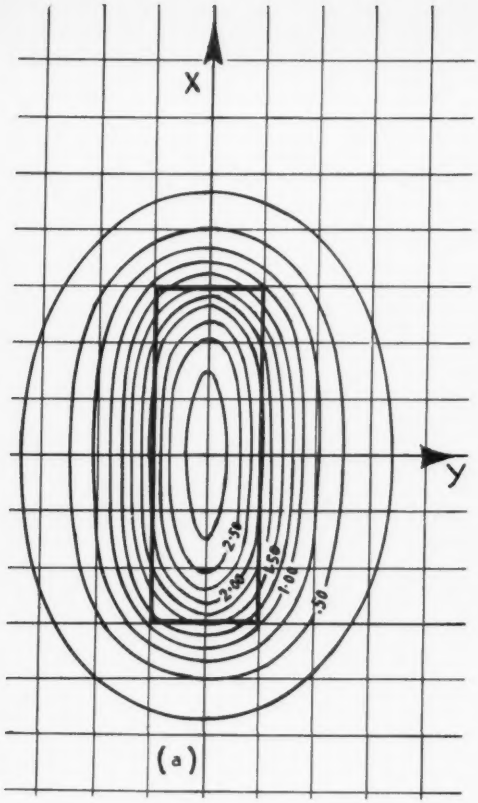


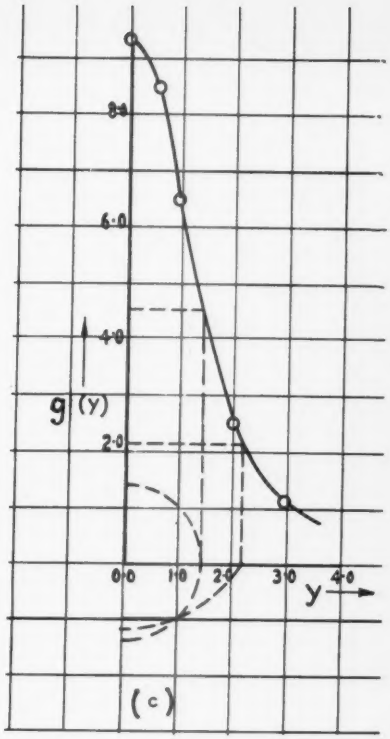
FIG. 5. Variation of distance between half-maximum points with apparent width $2L(\equiv 2l \cos\beta)$ for total intensity anomaly profiles of infinitely long vertically polarized strips along magnetic east-west. All distances in units of depth. Use solid curve. Meaning of dashed lines as in Figure 4.

be readily interpreted by Egyed-Jung's construction and the four unknowns ascertained. Figure 6 is a numerical illustration where the anomaly caused by a rectangular lamina with 6:2:1 as the length:width:depth ratio has been interpreted by this technique. The interpreted ratio of 5.76:1.96:0.98 checks very well with that theoretically assumed.

VERTICAL MAGNETIC FIELD OF A FINITE VEIN

While the interpretation of vertical magnetic anomalies caused by infinitely long magnetizable veins has received a great deal of attention in geophysical literature (Gulatee, 1938, for example), the problem of finite veins has not been adequately dealt with. It can be demonstrated and it is intuitively clear that the effect of applying the transform in the direction of magnetization (that is, the magnetic meridian) is to eliminate entirely the contributions from the horizontal component of magnetic polarization. After such a transform, the body may be deemed to have been magnetized by a vertical inducing field only. The procedure is best understood with reference to Figure 7, in which (a) shows the vertical magnetic field contours of a vertical vein striking eastwest, having a length:breadth:depth ratio equal to 6:2:1 and placed in an inducing field of inclination 45 degrees. An integration along the magnetic meridian (y, in this case) yields the symmetrical profile in Figure 7(b), caused by a hypothetical infinite strip at the same depth and having a width equal to the length of the actual vein. Egyed-Jung's construction gives the length of the vein to be 5.90 units and depth 0.99 unit.





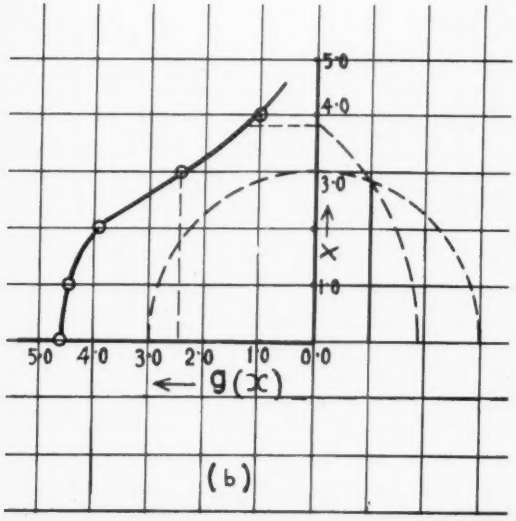


FIG. 6. (a) Vertical magnetic (or gravity) anomaly contours of a horizontal rectangular sheet six units in length, two units wide and one unit in depth (Vacquir *et al*, 1951, Figure A78). (b) Profile after integration along width and its interpretation. (c) Profile after integration along length and its interpretation.

The result of an integration along the eastwest direction (along strike) is to replace the finite vein by an infinite one of the same width, depth and dip. The corresponding anomaly profile is shown by a solid line in Figure 7(c). A comparison with the standard curves of Gulatee gives the width as two units, depth as one unit, dip of vein as 90 degrees and inclination of inducing field as around 45 degrees.

If the vein has an azimuth different from 0 degrees or 90 degrees with reference to the magnetic north, the interpretation cannot be quite so simple. In such a case, it is permissible to integrate only along and perpendicular to the strike, and *not* along the magnetic meridian. This ensures that every cross-section of the body along a direction of integration remains the same, a condition that has been scrupulously maintained in all the examples cited so far. The integration along the strike retains the width, depth and dip of the original body, whereas that across the strike retains the length and the depth only (the dip being 90 degrees). Both of these (integrated) profiles are to be interpreted by comparison with standard curves or such other methods available for dealing with infinite veins. The rectangle formed by the intersection of the top surfaces of the two imaginary infinite veins is the location of the real body. For an arbitrary azimuth, a meridianal integration is advisable only if the vein is thin.

SELF POTENTIAL OF A FINITE VEIN

The integral transform applied along the length of the finite vein will, as usual, convert it to an infinite one. This can then be interpreted by the method developed by Roy and Chowdhuri (1959). In this case, evaluating the transform in any other direction does not seem to be of particular use.

APPLICATION TO PROBLEMS OF DC ELECTRICAL PROSPECTING: INCLINED CONTACT

We will now consider a different class of problems where the transform (1a) or (1b) also promises to be useful. The complete solution for the potential when two different media of electrical resistivities ρ_1 and ρ_2 meet along a dipping interface $\theta=\alpha$ has only recently been furnished by Maeda (1955) and De Gery & Kunetz (1956). The problem is to find expressions for V_1 and V_2 (potentials in the two media) such that each of them satisfies Laplace's equation (z-axis coinciding with hinge line)

$$\frac{\partial^2 V}{\partial r^2}+\frac{1}{r}\frac{\partial V}{\partial r}+\frac{1}{r^2}\frac{\partial^2 V}{\partial \theta^2}+\frac{\partial^2 V}{\partial z^2}=0, \quad (17)$$

the boundary conditions

$$\left.\begin{aligned} \frac{\partial V_1}{\partial \theta}&=0 \text{ at } \theta=0\\ \frac{\partial V_2}{\partial \theta}&=0 \text{ at } \theta=\pi\\ V_1&=V_2 \text{ at } \theta=\alpha\\ \frac{1}{\rho_1}\frac{\partial V_1}{\partial \theta}&=\frac{1}{\rho_2}\frac{\partial V_2}{\partial \theta} \text{ at } \theta=\alpha \end{aligned}\right\}, \quad (18)$$

and the condition at the source, viz,

$$V_1=\frac{\rho_1 I}{2\pi}\cdot\frac{1}{R}$$

$$R=(r^2+r_0^2-2rr_0\cos\theta+z^2)^{1/2}. \quad (19)$$

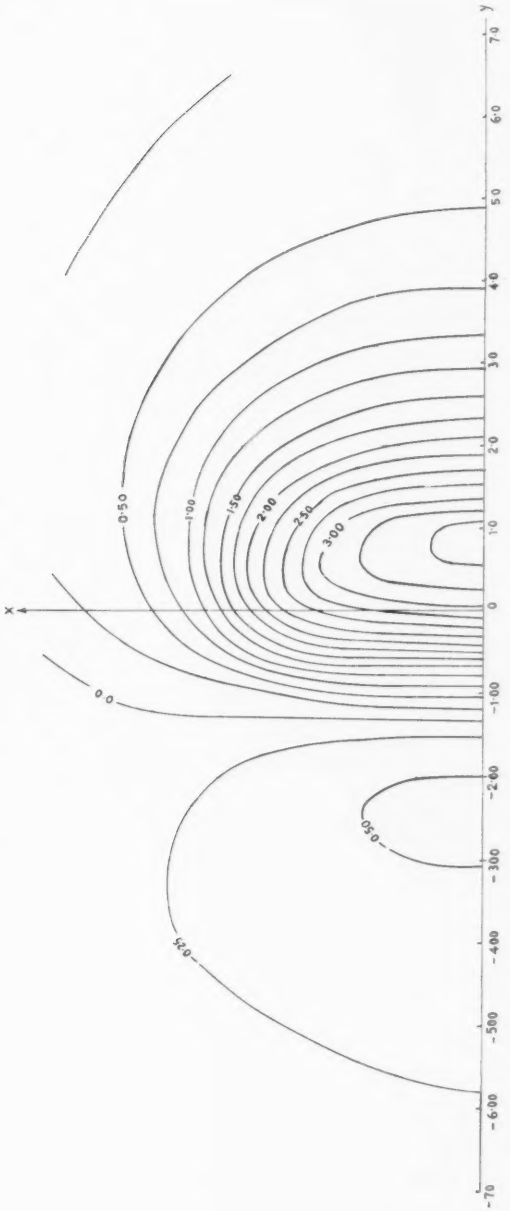
In the above, I is the current strength of the point source located at $r=r_0$, $\theta=0$, $z=0$. Let us now apply the integral transform to this problem, that is, to (17), (18) and (19), along the z direction. Since, by the bilateral symmetry of the problem, $\partial V/\partial z=0$ at $z=-\infty, 0$ and ∞, equation (17) is transformed to

$$\frac{\partial^2 \overline{V}}{\partial r^2}+\frac{1}{r}\frac{\partial \overline{V}}{\partial r}+\frac{1}{r^2}\frac{\partial^2 \overline{V}}{\partial \theta^2}=0,$$

$$\text{where } \overline{V}(r,\theta)=\int_{-\infty}^{\infty} V(r,\theta,z)dz. \quad (20)$$

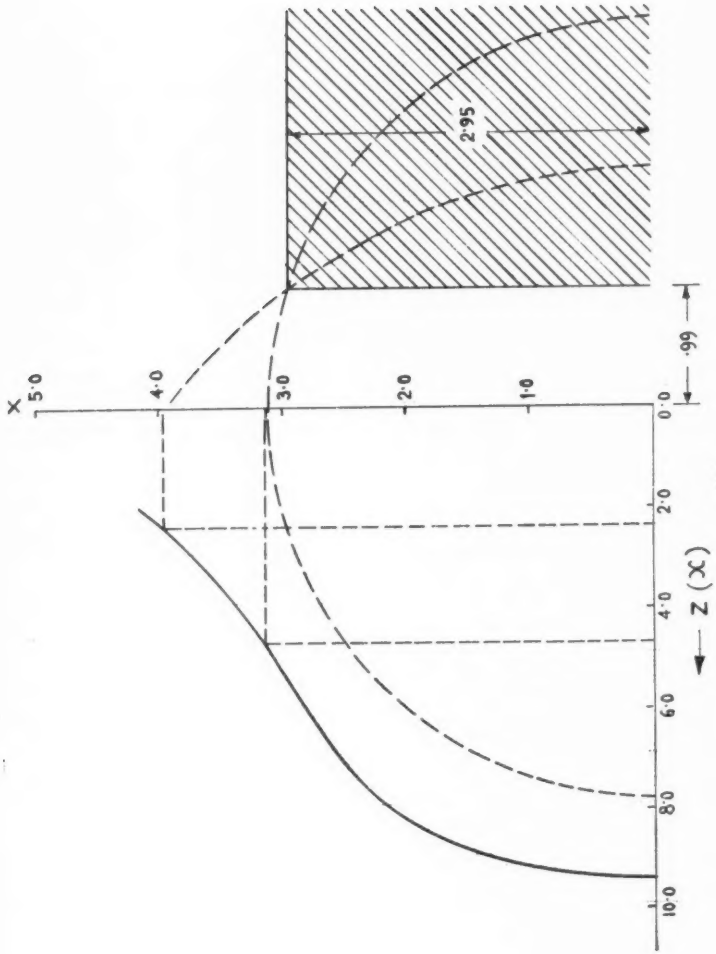
The transformed boundary conditions under (18) are simply

$$\left.\begin{aligned} \frac{\partial \overline{V}_1}{\partial \theta}&=0 \text{ at } \theta=0\\ \frac{\partial \overline{V}_2}{\partial \theta}&=0 \text{ at } \theta=\pi\\ \overline{V}_1&=\overline{V}_2 \text{ at } \theta=\alpha\\ \frac{1}{\rho_1}\frac{\partial \overline{V}_1}{\partial \theta}&=\frac{1}{\rho_2}\frac{\partial V_2}{\partial \theta} \text{ at } \theta=\alpha \end{aligned}\right\}. \quad (21)$$



(a)

FIG. 7. *(Continued on following pages. See legend on page 239.)*



(b)

FIG. 7 (*Continued on next page.*)

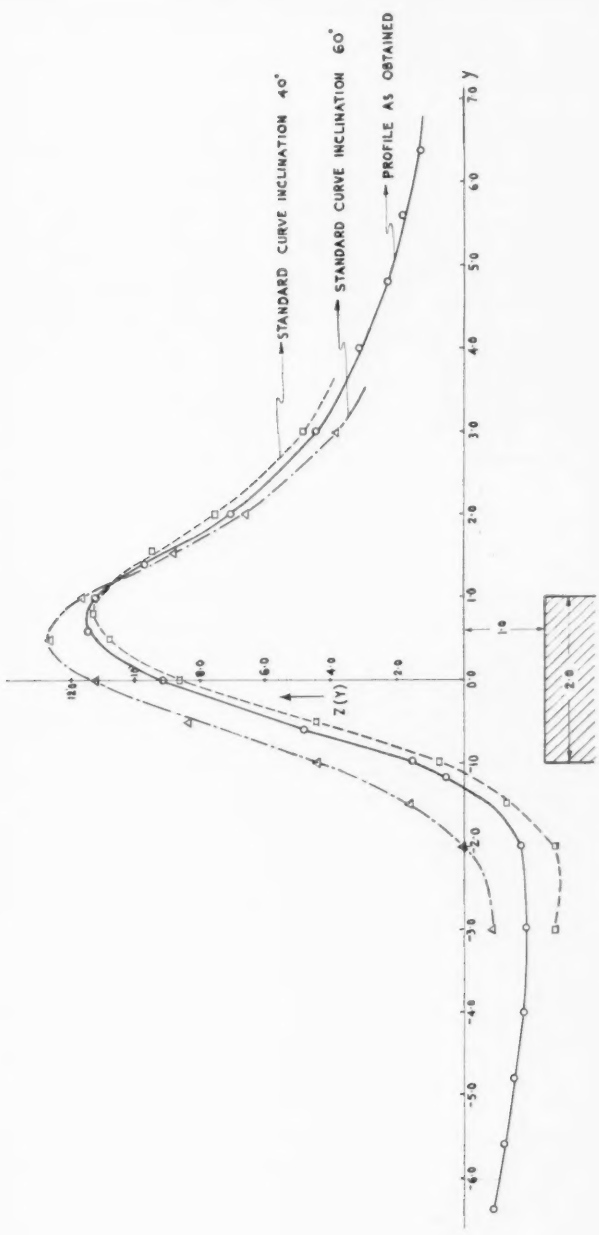


FIG. 7. (a) Vertical anomaly contours (in units of kT, where k is susceptibility contrast) of finite eastwest vertical vein with length: width: depth equal to 6:2:1. Inclination of inducing field 45 degrees. (b) Symmetric solid line profile obtained by meridianal integration, and its interpretation. (c) Profile (solid line) resulting from integration along strike and its interpretation.

For (19), we get

$$\overline{V}_1 = \frac{\rho_1 I}{\pi}\,[c - \ln \overline{R}],$$

$$\overline{R} = (r^2 + r_0^2 - 2rr_0\cos\theta)^{1/2}, \tag{22}$$

where c is an infinite constant. For the integration, one has to remember, of course, that R is an even function of z. An examination of the transformed problem reveals that the effect of applying the transform has been merely to substitute the point source of current I by an infinite line source parallel to the hinge and having a current strength of I per unit length. The shape, size, position and the physical properties of the body that is being prospected for remain unaltered. As before, a three-dimensional problem has been reduced to a simple one in two dimensions. The solution of the problem is (Smythe 1950)

$$\overline{V}_1\Big|_{\theta=0} = \frac{\rho_1^2 I}{2\pi^2}(1+\beta)\int_0^\infty \frac{\cos(\lambda \ln r/r_0) - 1}{\lambda[\sinh\lambda\pi + \beta\sinh\lambda(\pi - 2\alpha)]}\,d\lambda, \tag{23}$$

$$\overline{V}_2\Big|_{\theta=\pi} = \frac{\rho_1^2 I}{2\pi^2}\int_0^\infty \frac{[\cosh\lambda\pi + \beta\sinh\lambda(\pi - 2\alpha)]\cos(\lambda\ln r/r_0) - (1+\beta)}{\lambda[\sinh\lambda\pi + \beta\sinh\lambda(\pi - 2\alpha)\ 1}\,d\lambda, \tag{24}$$

with $\beta = (\rho_2 - \rho_1)/(\rho_2 + \rho_1)$. It is interesting to compare (23) and (24) with Maeda's solution, which is

$$V_1\Big|_{\theta=0} = \frac{\rho_1 I}{2\pi}\left[\{r - r_0)^2 + z^2\}^{-1/2} + \frac{4}{\pi^2}\int_0^\infty \cos tz dt \times \int_0^\infty \frac{\beta\sinh 2s(\pi - \alpha)}{\sinh s\pi + \beta\sinh s(2\alpha - \pi)} K_{is}(tr_0)K_{is}(tr)ds\right], \tag{25}$$

$$V_2\Big|_{\theta=\pi} = \frac{\rho_1 I}{2\pi}\left[\{r + r_0)^2 + z^2\}^{-1/2} + \frac{4}{\pi^2}\int_0^\infty \cos tz dt \times \int_0^\infty \frac{\beta[\sinh s\pi - \sinh s(2\alpha - \pi)]}{\sinh s\pi + \beta\sinh s(2\alpha - \pi)} K_{is}(tr_0)K_{is}(tr)ds\right]. \tag{26}$$

In (25) and (26), $i = \sqrt{-1}$ and K_{is}'s are the modified Bessel functions of the second kind and imaginary order. It is obvious that the difficulties and the amount of labor involved in the numerical computation of master curves from the above integrals are much greater in the conventional approach. Once the field values of the potential (with point source) are integrated along the strike direction, the resulting profile can be interpreted for all the unknowns of the original problem simply by matching it with the theoretical master curves of the two-dimensional problem.

CYLINDRICAL ORE BODY IN PRESENCE OF A POINT SOURCE OF CURRENT

For the present, we will just indicate the usefulness of the transform in relation to one more problem in electrical prospecting. For the theoretical solution of a cylindrical (circular) orebody in presence of a point source of current, one has to deal with the Laplace equation in cylindrical bipolar coordinates, viz,

$$\frac{\partial^2 V}{\partial\xi^2} + \frac{\partial^2 V}{\partial\eta^2} + \frac{a^2}{(\cosh\xi - \cos\eta)^2}\frac{\partial^2 V}{\partial z^2} = 0, \tag{27}$$

with $-\infty < \xi < \infty$ and $0 \le \eta \le 2\pi$, and with the usual set of boundary and source conditions. Unfortunately, equation (27) cannot be solved because the variables (ξ, η) are not separable. The problem thus defies a theoretical solution, and quantitative interpretations cannot be done except through model tank experiments. The application of the transform along the z-direction (axis of cylinder), however, reduces (27) to the simple two-dimensional bipolar Laplace equation

$$\frac{\partial^2 \overline{V}}{\partial \xi^2} + \frac{\partial^2 \overline{V}}{\partial \eta^2} = 0, \tag{28}$$

which can be readily solved. The boundary and the source conditions, of course, are accordingly modified.

CONCLUSIONS

It is hoped that the various types of problems treated in the text suffice to demonstrate the use and the advantages of the simple integral transform. The checks between the theoretical values and those obtained after interpretation by this method are quite striking. It appears, though this has not been investigated, that the effect of random or observational errors will be reduced in the process of integration.

In problems of electrical prospecting typified by the last two examples, the transform does what a prospector can achieve by the very difficult process (if at all practical) of using a long straight line DC source parallel to the long axis. In other words, in the field one can use the convenient-to-handle point source, while for the interpretation of the same data, one can analyze the convenient-to-solve two-dimensional problem. This, however, implies that the field data cannot be collected in the manner of a conventional resistivity method, but the potential measurements need to be made, preferably in a grid pattern, over the entire area just as in gravity, magnetic, S.P., telluric and some of the other methods.

It has been seen that some of the problems become susceptible to theoretical analysis and quantitative interpretation only after the transform has been taken. Since the transformation makes them purely two-dimensional, the powerful technique of conformal mapping becomes available.

It seems likely that the application of the transforms can be extended to similar problems in electromagnetic prospecting.

ACKNOWLEDGEMENT

We are indebted to Sri J. G. Negi who has solved some of the intricate integrations, and to Sri N. G. Sarkar who has done the excellent drafting of the figures.

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DEPARTMENTS

DISCUSSIONS AND COMMUNICATIONS

CORRECTION TO THE PAPER, "WATER REVERBERATIONS—THEIR NATURE AND ELIMINATION" BY M. M. BACKUS*

F. KALISVAART† AND A. J. SERIFF†

On page 240 of this very useful and stimulating paper, there appears to be an error in equation (14). The multiplier representing the number of different permutations of the ray-path segments for a given j, k, n is given as

$$\frac{(n+j-k)!}{(j-k)!n!}, \tag{1}$$

and this formula has apparently been used to compute the curves in Figures 7, 8, and 9. The number of permutations is actually larger and is given by the multiplier

$$\frac{(j-1)!}{k!(j-k-1)!}\,\frac{(n+j-k)!}{(j-k)!n!}. \tag{2}$$

Since these multipliers are identical for $k=0$ and $k=j-1$, the examples in Figure 6 and the curves in Figures 7, 8, and 9 for $j=0$, 1, and 2 are correct. For $j\geq 3$, sizable differences do occur; however, the qualitatively important features of the curves given do not change.

The multiplier given in (2) can be easily derived as follows. The multiplier is simply the number of recognizably different ways in which j identical objects of a first type, k identical objects of a second type, and n identical objects of a third type can be arranged in sequence with the added restriction that the k objects must always be placed *singly between* two of the j objects. It can be shown that any such ordering of the j, k, and n reflections will have the proper total path length and the correct number of reflections and transmissions at the water-solid interface.

Now, we see that there are $j-1$ intervals between the j-type reflections where a k reflection can occur, and hence there are

$$\binom{j-1}{k}$$

different arrangements of these two types of events. For each of these arrangements, there are $[(j-1)-k+2]$ remaining places where zero, one, or more reflections of the n type can occur. The "2" results from the fact that n-type reflections can precede or follow all of the j. Now, the number of distinguishable ways the n identical reflections can be placed in the $j-k+1$ permissible positions is just[1]

$$\binom{j-k+1+n-1}{n}.$$

Thus, the total number of different arrangements of all three types of reflections is just the product of these two binomial coefficients

$$\binom{j-1}{k}\binom{j-k+n}{n}.$$

[1] See, for instance, Feller, W., 1957, An introduction to probability theory and its applications, I: Second Edition, John Wiley & Sons, Inc., New York, p. 36.

* Backus, M. M., 1959, Water reverberations—their nature and elimination: Geophysics, v. 24, p. 233–261.

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REVIEWS

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CONTENTS

AAPG Slide Manual, William R. Moran, by *Dorothy A. Adams* 243
The First Big Oil Hunt—Venezuela 1911–1916, Ralph Arnold, George A. Macready, and Thomas W. Barrington, By *F. W. Johnson* 243
Principles of Geochemical Prospecting, I. I. Ginzburg, By *Hari Narain* 245
Methods and Case Histories in Mining Geophysics, Canadian Institute of Mining and Metallurgy, By *John S. Sumner* 245
The Gravity Field of the Venezuelan Andes and Adjacent Basins, J. Hospers and J. C. Van Wijnen, By *Roland G. Henderson* 246
Statistical Theory of Communication, Y. W. Lee, By *Mark Holzman* 247
Scientific Russian, George E. Condoyannis, By *Carl H. Savit* 247

AAPG Slide Manual, A.A.P.G. Committee on Preparation of Projection Slides, William R. Moran, Chairman, American Association of Petroleum Geologists, Inc., Tulsa, 1960, 27 pp., $1.25.

From the foreword: "This booklet is designed to bring together basic information about the preparation of copy for slides and transparencies, their production, and their use in the presentation of technical papers."

It is the aim of the authors to improve the "effectiveness of visually projected information" for A.A.P.G. talks.

Experienced slide makers will use the manual as a handy reference. They should also be familiar with the A.A.P.G. visual standards. The speaker without an experienced draftsman to assist him will find that, with the many aids and suggestions, he can more easily make a good slide than a bad one.

Manufacture of slides is briefly discussed to enable the reader to give intelligent instruction to the photographer. Projectors, screens, audience seating, and pointers are also reviewed. Members of all arrangements committees should certainly read the book.

This manual is well thought out and carefully researched. A bibliography is included for those interested in proceeding beyond the scope of the book.

This book is a must for every drafting room in which slides are made. The quality of illustrated lectures should improve in direct proportion to the distribution and use of this manual.

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The First Big Oil Hunt—Venezuela 1911–1916, Ralph Arnold, George A. Macready, and Thomas W. Barrington, Vantage Press, New York, 1960, 353 pp. $10.00.

This book is unusual in that not only did its three main authors have the distinction of participating in the early petroleum exploration in Venezuela and Trinidad, but it also includes the contributions of 23 others. All were members of a team which carried out geological surveys in a country which was much as it was in colonial times. Fine photographs of contemporary scenes and the pioneer operations in Venezuela and Trinidad add to the excellent documentation. These men were young, fresh out of the classrooms of the leading universities of the United States. Many suffered from malaria, typhoid, yellow fever, and other

tropical diseases. They worked under unusual conditions including contacts with the friendly, nomadic Indians of the desert-like Guajira peninsula. They carried on a running battle with the unfriendly, warlike Motilones of the humid jungles of the southwestern Maracaibo basin. Their record includes an exciting account of attack by this hostile tribe. However, they found most Venezuelans friendly, cooperative and interested. This was of inestimable value to the success of their and subsequent operations in Venezuela.

Dr. Arnold entered Trinidad in 1911 as a result of a personal recommendation by Herbert Hoover to the Goldfields of South Africa, Ltd. After a quick reconnaissance of Trinidad, he returned to New York and was engaged by the General Asphalt Company. His job was to find oil and bring it out of the ground in order to fill their empty tankers, and, secondly, to discover and lay claim to every single piece of potential oil land in Venezuela. This survey eventually involved 52 American geologists.

Success came early. A well in Trinidad blew out in July, 1912, at the rate of 15,000 barrels a day. It soon sanded up, but was followed by a prolific producer and the development of the Vessigny field, the first in Trinidad to show an operating profit.

General Asphalt had operations at the Pitch Lake in Trinidad and at Guanoco in Venezuela. Venezuela had produced some oil as far back as 1878 in the Andes. Also, a few wells had been drilled around the asphalt lakes of eastern Venezuela but no serious regional geological surveys had been made. This company obtained acreage in 1910 at Guanoco and later, in 1912, acquired concessions covering practically the whole area of Venezuela north of the Orinoco and Apure rivers with the exception of a few central states.

Many of the oil seeps of eastern Venezuela were visited in 1912, including Quiriquire where a large oil field now exists. Floyd C. Merritt and Garnett A. Joslin were in the first field party to get into the now famous Maracaibo basin. They encountered the large seeps around what is now the Bolivar Coastal field and Mene Grande.

This book includes Arnold's first report on the concessions of the Caribbean Petroleum Company in which he outlined the geological framework of Venezuela. This was written after Arnold, Macready and their associates had been working in Venezuela less than one year, during which time they had assimilated a good picture of the general geology of that nation, a country roughly 1,000 miles long, east and west. This information was obtained as a result of work under extremely difficult conditions, primitive roads, poor transportation, and little or no communications with the exception of a fair telegraph system. Arnold drew upon Macready's report as a basis for recommending acreage in the vicinity of Mene Grande stating that "it indicates a well-defined zone or zones of oil sands in the Tertiary series that underlies the region about Lake Maracaibo." He boldly recommended the selection of 12,000 hectares surrounding these great seepages, and made the location of well Zumaque-1 which resulted in the discovery of the Mene Grande field on April 15, 1914. This historic report, dated November 27, 1912 was a short, concise, and highly important document. Subsequent to its submission to the General Asphalt Company of Philadelphia, the Venezuelan acreage was offered to various oil companies of the United States—none were interested. As a last resort, the report was taken to the Royal Dutch Shell Oil Company in London and they paid $10 million for 51 percent of the General Asphalt Company's Caribbean Petroleum Company. This decision was made by Sir Henry Deterding. He later stated that he had made "perhaps the most speculative venture of my life when on behalf of our companies I bought from the General Asphalt Company, of Philadelphia, a long term concession which had been granted to it covering enormous areas in all parts of the country." He further stated "I admit to having been impressed by a favorable report from that expert American geologist, Dr. Ralph Arnold, on the potential value of these huge fields and I had faith in the representatives who came to London from Philadelphia to negotiate the deal."

Exploration by Arnold and his crews continued until 1916. Copies of a number of the plates from these reports are included in the text. One of the most interesting shows a generalized east-west cross-section showing the existence of an anticline in Lake Maracaibo. Oil is postulated as being accumulated in the truncated sediments underlying an unconformity as well as in the overlying section. This is probably the first geological interpretation showing such a structure and the postulation of a petroleum accumulation under Lake Maracaibo. The huge Bolivar Coastal field exists under conditions very similar to those shown on this plate.

The authors also included very interesting accounts of their experiences which led to the discovery of the Tarra and La Paz fields.

The book contains numerous human interest sidelights such as Barrington's directive "to do anything I could for Theodore Roosevelt while he and his wife were visiting Trinidad," or the account of an American consul who insured his tenure in Maracaibo by keeping a coffin protruding from under the bed, and remarking to a newcomer "that a coffin was always kept handy because of the prevalence of yellow fever and necessity of immediate burial." The newcomer generally returned immediately to the States.

There is also a description of a face-to-face meeting, far back in the sticks, with the noted British geologist, E. H. Cunningham-Craig, who was outfitted completely with cork helmet, high laced boots and crooked

handled walking stick—all considered essential to the 1912 geologist working in the tropics. Another is an eyewitness account of the birth of a new island off the coast of Trinidad, which, during its formation, exploded into flames 300 to 400 feet high. An estimated 700,000 tons of dirt were blown out of the lower Tertiary through two craters.

Tribute is given to Don Santiago Aguerrevere, dean of Venezuelan Civil engineers, who was employed as official engineer and had charge of all surveys. Three of his sons later graduated from Stanford, two in geology and one as a civil engineer. These men of high integrity had important parts in the establishment of a fine relationship between the company and the land owners. They later held high positions in the Venezuelan government. Pedro Aguerrevere counseled the revision of the agreements between the companies and the government, an idea which evolved into the Petroleum Law of 1943, and he was later Minister of Fomento in the late 1940's. He followed a policy of trying to solve the problems of national interest with the oil and mining companies "in a spirit of reciprocal fair play and practical understanding."

These early oil hunters were men of indomitable spirit, possessing the urge to explore and a desire to participate in a great development of free enterprise. They had the courage to work under the most serious of health and physical handicaps. They were true pioneers of petroleum exploration in a vast area nearly 1,000 miles from east to west. It must have been a great satisfaction for them to see the fruits of their early labors grow into a vast industry which has accelerated the transformation of a poor, underfed and underdeveloped country into an energetic, restless nation going through a great period of readjustment in finding its place in the modern world.

The authors of *The First Big Oil Hunt* have made a major contribution to the history of the petroleum industry in putting on record their experiences. It will serve as a reference for all time. It is a book which anyone, particularly those who have worked in Venezuela, will read with absorbing interest.

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Principles of Geochemical Prospecting, I. I. Ginzburg, Pergamon Press, New York and London, 1960, xviii+311 pp., $11.50.

Principles of Geochemical Prospecting for non-ferrous ores and rare metals is the outcome of many years of study of the fundamental principles of ore formation, dispersion, accumulation and association with accessory elements. Although a good number of books on diverse aspects of geochemical prospecting for minerals have been published earlier, this book is the first of its kind to cover the entire subject of geochemical prospecting for minerals including hydrochemical, biogeochemical and geobotanical techniques.

Chapter I has been devoted to discussion of the limitations of the different analytical procedures commonly in use. "Rational" analysis might be useful in broadly delineating mineralized provinces but its weakness, such as the absence of suitable reagents to decompose all ore bodies, especially those locked in the silicate grains, limits its use in detailed surveys. Techniques like paper-chromatography, ion-exchange resins, spectrometry, colorimetry, etc., each has its own limitations and thus the choice of a method needs to be predetermined for each particular type of test material.

Chapter II has been devoted to geochemical indicators to evaluate definite horizons of sedimentary rocks, mineralized bodies of diverse origin, and polymetallic deposits. Chapters III to VIII have been devoted to detailed theoretical aspects of accumulation, dispersion tendencies of the elements, and the factors affecting them in different rock types. Examples have been cited, particularly with reference to work carried out over the Russian platform in support of the success of geochemical prospecting in different rock bodies. Besides their usefulness in prospecting, geochemical indices are of considerable help in correlation of sedimentary rock horizons. Chapters IX and X deal with migration of metals in waters and hydrogeochemical prospecting. Chapters XI and XII are devoted to biogeochemical and geobotanical methods of prospecting. General conclusions in reference to geochemical surveys have been drawn in concluding Chapter XIII.

As an advanced treatise, explaining in clear language the various problems encountered in geochemical prospecting for ores and metals in different formations, this book will be useful both to the research worker and to industry. Of considerable importance are the chapters where fundamental principles of the techniques have been described. The wealth of references to the literature will be of particular value for future development and refinement of techniques. It is evident, after a careful perusal of the book, that studies in this field are by no means completed and there is plenty of scope for further research.

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Methods and Case Histories in Mining Geophysics, arranged by a Committee of Geophysicists of the Canadian Institute of Mining and Metallurgy, Canadian Institute of Mining and Metallurgy, Montreal, 1959, viii+359 pp. +12 maps, $10.00.

This volume is devoted primarily to case histories in

mining exploration in the Canadian Shield. Also included is an important collection of papers on theory and methods of relatively modern mining geophysical practices. Field procedures and pitfalls of the geophysicist are aptly covered.

The book is aimed toward the reader who is not well acquainted with geophysical theory, but who is concerned with the development of mineral resources. It was an outgrowth of the Sixth Commonwealth Mining and Metallurgical Congress held in Canada in 1957. Papers have also been drawn from other countries of the Commonwealth.

The editorial board consisted of 21 eminent geophysicists who have all had considerable experience in Canada's Precambrian Shield. There are a total of 14 articles covering regional geophysics and magnetic, gravitational, geochemical, radioactive, electrical, and refraction seismic exploration. Most of these subjects are treated by acknowledged experts in the methods. Case histories of 32 prospects and mines in Australia, Canada, Great Britain, India, Jamaica, South Africa, Tanganyika, and Uganda are given by authors who are intimately familiar with conditions of their problems. Types of deposits investigated include asbestos, copper, lead, zinc, gold, nickel, silver, titanium, iron, tungsten, manganese, coal, and ground water. Several of the case histories are classical examples of successes in mining discoveries.

Important introductory remarks are made by Prof. J. T. Wilson concerning regional geophysical settings of mineral districts. Perhaps the most valuable section of the book describes the various methods and procedures that have been used in mining geophysics. Rapid and recent progress in the development of mining geophysical equipment has created new instruments which were impractical in the past.

To illustrate the rapid strides which have been accomplished in the three years since this book was issued, two new methods have come into common use since publication. These schemes are induced polarization and AFMAG. The editors of this book include some of the principal contributors to these important techniques.

Case histories are generally well presented and give a good review of the planning, field work, interpretation of data, and drill results. Due credit is accorded to geology.

Two minor errors were noted concerning the iron content of rocks referred to on pages 206 and 215. The authors perhaps assumed that the content of iron ore is based on percent volume rather than percent weight. In this regard it is noteworthy that percent magnetite by volume of most low grade magnetic iron-formations is very nearly the percent iron by weight. This fact is useful in relating magnetic susceptibility to grade of magnetic iron ore.

This volume is strongly recommended for reading by anyone who is technically associated with mining geophysics. Much of the material covered such as typical ground and airborne electromagnetic systems is not to be easily found elsewhere. There is also contained here a wealth of data on physical properties of rocks.

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The Gravity Field of the Venezuelan Andes and Adjacent Basins, J. Hospers and J. C. Van Wijnen, *Verhandelingen der Koninklijke Nederlandse Akademie van Wetenschappen, Afd. Natuurkunde*, Vol. 23, No. 1, 1959, pp. 1–95.

The senior author has already made valuable contributions to an understanding of the gravity field in the Alps and in northern South America and the West Indies as well. This joint effort is a clearly-written, well-illustrated report of gravity investigations in a structural province comprising the Venezuelan Andes and the adjacent Maracaibo and Barinas-Apure basins. The work is oriented more towards a study of tectonic and orogenic phenomena than towards exploration; nevertheless, anyone with a modicum of interest in gravity and structural geology will find it excellent reading.

A special gravity survey carried out along main highways in the central Venezuelan Andes was tied to an earlier network outside the Andes. Exact positions and observed values are given for certain gravity stations which should be useful for possible future surveys. In the Bouguer correction the gravity effect of a spherical plateau is used rather than that of a horizontal slab of infinite extent. The Bouguer anomalies are regarded first as an intermediate step in the calculation of isostatic anomalies and second as a representation of mass irregularities below sea level. Isostatic corrections were computed for eleven selected stations for three systems of local compensation according to the Airy-Heiskanen hypothesis and six systems of regional compensation according to the Vening Meinesz hypothesis.

A comparison of magnitudes of Bouguer anomalies and isostatic corrections computed for the nine systems at selected stations indicates that no single system of compensation is appropriate to all stations; that there is a pronounced gravity deficit in the Maracaibo basin; and that in the Venezuelan Andes there is predominantly regional compensation in the southeastern range, and local or weak regional compensation in the northwestern range. Computations suggest that there exist crustal downwarps in the basins and an asymmetrical mass distribution underneath the Andes. The authors believe that, under lateral compressive forces, thrust faults developed in the crust so that the southeastern part was thrust over the northwestern part. With the application of a "geological correction" and

a "geological isostatic correction," the isostatic anomalies tend to support the shear-fracture hypothesis advanced. The orogenic theories of Vening Meinesz (plastic buckling) and of van Bemmelen (undation) are considered, but after some terse reasoning involving comparisons with the Alps and the inferred absence of hypodifferentiation, they conclude that neither played an important role in the tectogenesis. An attempt was made to determine the direction of the orogenic compressive stress but this is admittedly unsatisfactory because the time element cannot be taken into consideration. The enlightening digressions on orogenic theories provide the reader with somewhat of a basis for evaluating the authors' theories concerning the Venezuelan Andes.

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Statistical Theory of Communication, Y. W. Lee, John Wiley & Sons, Inc. New York, 1960, xvii+509 pp., $16.75.

Prior to the development of statistically motivated communication theories some twenty years ago, the communication engineer had two classical tools at his disposal for dealing with signal and noise problems: the Fourier series and the Fourier integral. Indeed, all those cases which could properly be characterized as being either "periodic" or "transient" were fully amenable to treatment by Fourier methods.

Powerful and versatile as these methods were, however, their province of mathematical validity excluded from consideration a large and important class of signals (and noise) which could not be categorized as either periodic or transient. Thus, the need for a generalization of the Fourier methods to allow for the inclusion of random phenomena became dramatically obvious.

Professor Lee begins his book with a thorough exposition of Wiener's theory of generalized harmonic analysis. Next, after several chapters dealing with selected topics from the theory of probability, the author takes up numerous practical problems which may well need consideration in adapting the theory to physical systems. The physical systems, *per se*, are not discussed. At this point, the serious reader has acquired sufficient background to appreciate the author's masterful exposition of Wiener's theory of optimum linear filtering, culminating in the Wiener-Hopf equations. The latter discussion is confined to rational spectra, thus minimizing analytic complexities which might otherwise tax the beginning reader. In anticipation of the reader's future needs, Dr. Lee devotes the last two chapters of his book to a discussion of orthonormal functions and their uses. It may be pointed out here, that these functions form an important bridge between Wiener's theory of linear systems and his more recent theory of optimum non-linear systems.

The present volume is an outgrowth of a one semester, first year graduate course, which Professor Lee has organized and taught in the department of electrical engineering at M.I.T. since 1947.

Many readers will welcome this book for several of its features: (1) emphasis in the treatment is not on the abstract ideas, but rather on their physical meaning and interpretation; (2) mathematical ideas are developed in great detail, with many of the intermediate steps shown (e.g. Five pages are devoted to a comparison of the convolution and the cross-correlation integrals); (3) numerous illustrations and worked-out problems are generously supplied throughout the text (e.g. Several examples of autocorrelation and cross-correlation are worked out analytically as well as graphically); (4) due to its clarity of exposition, the book is ideally suited for self study.

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Scientific Russian, George E. Condoyannis, John Wiley and Sons, Inc., New York, 1959, xii +225 pp., $3.50.

Nearly all language books and language self-teachers are written on the assumption that the user desires to learn to speak or write the language. *Scientific Russian*, on the other hand, is designed as a self-teacher for the scientist or engineer who wishes to learn to read technical papers in Russian. In a sense, it may also be classed as an "on the job training manual" for the do-it-yourself reader of technical Russian. One complete reading of the book, which should take no more than four or five hours, will enable one to start translating Russian technical material, albeit slowly and painfully, with the aid of a dictionary.

Certainly no one can suddenly become proficient in a language. *Scientific Russian* cannot, therefore, be expected to provide a "royal road" to Russian reading. To become proficient at Russian translation, it would still be necessary to work carefully through the exercises in the book and to practice translating actual technical material.

Since Professor Condoyannis is interested in teaching the reading of Russian, he approaches the language from a recognition standpoint, that is, he presents the grammar and vocabulary entirely from the view-point of one attempting to determine from a given Russian word or phrase, what that word or phrase means. Verbs, adjectives, prepositions, pronouns, prefixes, suffixes, etc. are presented in tabular form for easy reference. Simple rules are given to make apparent the English, French, or German words from which many Russian words are derived.

As with any first edition, *Scientific Russian* contains

its share of typographical errors. Some of them are more than slightly troublesome, particularly the occasional absent or scrambled footnotes which are supposed to explain obscure points. All in all, however, this plastic-bound handbook is highly recommended as the best book known to this reviewer for the prospective reader of Russian technical material. Even those who have a considerable facility with the language will find both the tables and etymology of great value.

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PATENTS

O. F. RITZMANN†

ELECTRICAL PROSPECTING

U. S. No. 2,953,742. R. J. Herbold. Iss. 9/20/60. App. 9/4/57. Assign. One-third each to C. J. Hughes, W. E. Hughes, and L. M. Hughes, Jr.

Geophysical Prospecting Apparatus. A radio wave prospecting system in which a spark discharge generates electromagnetic waves in the earth whose reflections are picked up by an antenna and displayed on a c-r tube screen which is photographed with a camera, the camera shutter being actuated in timed relationship to the spark.

U. S. No. 2,955,250. J. L. M. Shaw and R. R. Taylor. Iss. 10/4/60. App. 10/24/57 and 3/21/58. Assign. The International Nickel Co., Inc.

Electromagnetic Prospecting. An airborne e-m prospecting system in which the plane carries two coplanar transmitting coils excited at different frequencies and a third orthogonal reference coil excited at a third frequency, and a towed bird carries similarly coplanar receiving coils and a reference coil coaxial with the third transmitting coil, the detected signals from the first two coils being compared with that of the reference coil.

U. S. No. 2,955,251. J. L. M. Shaw and R. R. Taylor. Iss. 10/4/60. App. 10/24/57 and 3/21/58. Assign. The International Nickel Co., Inc.

Geophysical Exploring. An airborne e-m prospecting system using two orthogonal energizing coils excited at different frequencies on the airplane or on a transmitting bird, and orthogonal pick-up coils on a detecting bird, and in which the relative position of the transmitting and detecting coils is maintained by means of a modulated light source on the transmitting vehicle acting on photocells carried on the detecting bird and which control servomotors that operate steering fins on the detecting bird.

GEOCHEMICAL PROSPECTING

U. S. No. 2,951,940. J. W. Graham and J. S. Osoba. Iss. 9/6/60. App. 3/1/57. Assign. Jersey Production Research Co.

Method of Ascertaining the Presence of Petroleum Deposits in Earth Formations. A method of detecting petroleum in drill chips obtained with drilling fluid free from fluorescing constituents and in which the chips are contacted with a cationic surface-active agent that causes preferential wetting of the chip surface by petroleum, and observing fluorescence of the chip under ultraviolet light.

U. S. No. 2,955,922. R. F. Christy. Iss. 10/11/60. App. 7/22/57. Assign. White Eagle International, Inc.

Gas Detection Apparatus. A combustible gas detector for a mud logging apparatus having a heated catalytic filament in a bridge circuit connected to a recorder.

GRAVIMETRIC PROSPECTING

U. S. No. 2,952,920. R. T. Cloud. Iss. 9/20/60. App. 1/22/57. Assign. North American Geophysical Co.

Ballast Compensated Pendulum. A horizontal torsion pendulum for an integrating elevation meter, the pendulum being a disk having a thin-walled buoyant chamber symmetrical with respect to the suspension wire, and the outer instrument housing filled with liquid and having a flexible wall portion through which pressure can be applied to the liquid which changes the volume of the buoyant chamber so as to compensate the symmetrical weight on the suspension.

U. S. No. 2,953,023. R. R. Goodell. Iss. 9/20/60. App. 7/26/57. Assign. Shell Oil Co.

Gravity Meter Clamp. A system for clamping a borehole gravimeter whose mass tensions a wire vibrating in vacuum and in which a linkage sealed by a metallic bellows actuates a wedge that separates two spring-biased fingers that clamp the mass.

RADIOACTIVITY PROSPECTING

U. S. No. 2,951, 941. H. R. Brannon, Jr. Iss. 9/6/60. App. 1/7/57. Assign. Jersey Production Research Co.

Method and Apparatus for Pulsing a Scintillation Detector. A radioactivity detector having a scintillating crystal and photomultiplier tube with a pulse of positive potential applied to a pair of dynodes to turn the photomultiplier on, and zero or negative potential applied when the photomultiplier is turned off.

U. S. No. 2,953,686. A. D. Garrison. Iss. 9/20/60. App. 9/15/54. Assign. Texaco Development Corp.

† Gulf Oil Corporation, Patent Department.

Detector of Penetrative Radiation. A radioactivity detector having an array of plates from which the incident radiation produces ionizing electrons in a continuously operating illuminated cloud chamber, and with the light scattered by the tracks detected by a photocell.

U. S. No. 2,955,207. A. Pearson. Iss. 10/4/60. App. 11/25/55. Assign. Atomic Energy of Canada Ltd.

Radiation Detector. An indicating circuit for a halogen-quenched Geiger-Muller tube in which the tube is connected to a cold-cathode trigger tube through a condenser with the current to the G-M tube and to the condenser arranged to flow through a common load whose current is indicated.

U. S. No. 2,956,162. F. C. Armistead. Iss. 10/11/60. App. 5/12/51 and 5/25/54. Assign. Texaco Development Corp.

Detection and Measurement of Penetrative Radiation. A radioactivity detector having a primary scintillating material optically coupled to a photocathode with a layer of secondary phosphor as a white powder on the surfaces of the primary phosphor away from the photocathode to reflect escaping fluorescence radiation onto the photocathode.

U. S. No. 2,956,164. J. R. Ford. Iss. 10/11/60. App. 9/4/56. Assign. Hycon Mfg. Co.

Airborne Scintillation Counter. An altitude-compensated airborne gamma-ray detector having a scintillating crystal and phototube with the amplified signal fed into parallel channel multivibrators which are set for different levels of firing thresholds and each connected to an altimeter that adjusts the output of each channel to compensate for altitude variations.

SEISMIC PROSPECTING

U. S. No. 2,952,006. E. R. McCarter. Iss. 9/6/60. App. 5/23/56. Assign. Jersey Production Research Co.

Attenuation of Seismic Signals. A seismograph avc system having an attenuator including a variable impedance bridge supplied with d-c obtained by rectifying part of the output signal, the rectified signal being applied to the bridge through two parallel circuit branches each of which has a rectifier and an adjustable resistor, and with the rectifiers in opposite polarity.

U. S. No. 2,952,812. W. W. Klein, Jr., W. W. Grannemann, and O. A. Fredricksson. Iss. 9/13/60. App. 1/27/56. Assign. California Research Corp.

Pulse Modulation Function Multiplier. A seismograph avc system in which a series of pulses are generated and modulated by a control function and also modulated by the seismic signal, and the dual-modulated signal demodulated in a single demodulator.

U. S. No. 2,952,833. T. Bardeen. Iss. 9/13/60. App. 11/14/55. Assign. Gulf Research & Development Co.

Monitoring System for Seismograph Filters. A system for recording on a seismogram the instantaneous adjustment of a time-varying filter by recording the output wave of an oscillator having a similarly varying frequency-determining element so that direct comparisons between the monitor frequency and the recorded reflections can be made on the seismogram.

U. S. No. 2,952,834. W. G. Noonan and V. L. Vice. Iss. 9/13/60. App. 11/28/55. Assign. Marine Exploration Co.

Seismic Exploration. A system for positioning the shot in marine seismic operations in which the detector cable has three supersonic receivers and the shooting boat has a supersonic transmitter that periodically transmits short pulses in the water in synchronism with a radio signal so that the travel time of the ultrasonic pulse can be used to locate the shot.

U. S. No. 2,953,214. E. Merten. Iss. 9/20/60. App. 2/27/57. Assign. Shell Oil Co.

Seismic Exploration. A system of seismic shooting in which a number of shots are placed at different depths in a common shot hole and detonated in succession from a common firing impulse, the successive shots having delay fuses that delay detonation of each charge until the reflections from the previous shot have been recorded.

U. S. No. 2,954,090. K. E. Burg and E. J. Stulken. Iss. 9/27/60. App. 7/28/53. Assign. Texas Instruments Inc.

System for Improving Seismic Records of Underground Strata. A system for eliminating reverberation in seismic prospecting in water-covered areas in which a sound-absorbing screen of gas bubbles is generated in the water by chemical or electrolytic action, slow-burning explosive, compressed air, or finely divided foam rubber.

U. S. No. 2,958,048. J. P. Woods. Iss. 10/25/60. App. 6/14/57. Assign. The Atlantic Refining Co.

Automatic Volume Control for Seismograph Signal Amplifier. A seismograph avc system in which the signal from one of the amplifier stages is rectified and used to control the output of a high-frequency oscillator whose signal is applied to nonlinear resistance elements in attenuator networks in both the input and output circuits of the amplifier stage.

See also Patents 2,951,736; 2,951,738; 2,957,167; and 2,958,010 listed under MISCELLANEOUS.

WELL LOGGING

U. S. No. 2,951,367. H. H. Rachford, Jr. Iss. 9/6/60.

App. 8/21/57. Assign. Jersey Production Research Co.

Process for Determining Fluids in Beds Traversed by Drill Holes. A thermal logging method in which a freezing mixture is placed in the borehole for a sufficient time to effect a change of state of formation fluids, the freezing mixture removed, and a succession of temperature logs run as the formations warm up.

U. S. No. 2,951,943. C. Goodman. Iss. 9/6/60. App. 5/7/56. Assign. Schlumberger Well Surveying Corp.

Borehole Investigating Apparatus. A radioactivity logging system having in the sonde a container of material capable of sustaining a controllable nuclear chain reaction and having protuberances that contact the borehole wall, a neutron reflector above and below the container, and a movable control strip carrying graduated neutron-absorbing material around the side of the container adjusted to hold the temperature of the reacting material constant, and a detector in the sonde to measure the radioactivity induced in the formations by the reaction.

U. S. No. 2,951,945. C. Goodman. Iss. 9/6/60. App. 5/26/54. Assign. Schlumberger Well Surveying Corp.

Renewable Target. An accelerator type neutron source whose target is a thin sheet of palladium sealed to a reservoir of tritium and provided with an electric heating element whose power is controlled in response to the neutron flux generated by the accelerator.

U. S. No. 2,951,946. H. B. Frey, Jr. Iss. 9/6/60. App. 11/9/55. Assign. Schlumberger Well Surveying Corp.

Method and Apparatus for Logging Earth Formations. A radioactivity logging system having in the sonde a container of uranyl sulphate dissolved in water and capable of sustaining a controllable nuclear chain reaction in the borehole, a neutron reflector above and below the container, and a movable control strip carrying graduated neutron-absorbing material around the side of the container, a radioactivity detector being used to monitor the power output and control the position of the control strip so as to maintain a constant power output, the position of the control strip being indicated at the surface.

U. S. No. 2,951,982. N. A. Schuster. Iss. 9/6/60. App. 7/22/55. Assign. Schlumberger Well Surveying Corp.

Systems for Electromagnetic Investigation of Media. An a-c resistivity logging system having a pad pressed against the borehole wall, the pad containing two energizing electrodes and a coil which is used to monitor and control the exciting current at a depth sufficient to be below the filter cake, the pad also containing two potential electrodes connected to a measuring circuit.

U. S. No. 2,952,019. C. Goodman. Iss. 9/6/60. App. 5/7/56 and 12/19/58. Assign. Schlumberger Well Surveying Corp.

Methods and Apparatus for Investigating Materials. A radioactivity logging system having in the sonde a subcritical mass of material capable of sustaining a controllable nuclear chain reaction and having protuberances that contact the borehole wall, a neutron reflector above and below the mass, and a movable neutron source that is adjusted in position so that the mass maintains a predetermined reaction power level, and a detector in the sonde to measure the radioactivity induced in the formations by the reaction.

U. S. No. 2,953,685. J. T. Dewan. Iss. 9/20/60. App. 6/16/55. Assign. Schlumberger Well Surveying Corp.

Well Logging. A neutron-gamma logging system using a polonium-beryllium source of relatively short life and in which the source-detector spacing is decreased as the source decays so as to keep the counting rate approximately constant.

U. S. No. 2,953,979. R B. Rosene and J. F. Eberhard. Iss. 9/27/60. App. 4/4/57. Assign. The Dow Chemical Co.

Well Bore Photography. A borehole camera in which a light source and a photographic or television camera is immersed in a transparent water and oil immiscible liquid of higher specific gravity than water.

U. S. No. 2,954,471. R. G. Piety. Iss. 9/27/60. App. 5/9/56. Assign. Phillips Petroleum Co.

Flow Measuring Apparatus. A well flow meter having a flexible packer bypassed by two flow paths one of which has a motor-driven impeller to increase the flow so that no flow occurs in the second path, and the speed of the motor is indicated at the surface, zero flow in the second path being determined by solution and detection of radioactive material.

U. S. No. 2,955,463. J. K. Godbey and H. D. Hodges. Iss. 10/11/60. App. 1/17/55. Assign. Socony Mobil Oil Co., Inc.

Logging System for Well Bores. A bottom-hole thermometer or pressure gauge in which the gauge adjusts a resistor in an oscillator circuit to vary its frequency, the oscillator signal being transmitted to the surface and its frequency measured.

U. S. No. 2,956,163. P. E. Baker. Iss. 10/11/60. App. 11/4/55. Assign. California Research Corp.

Nuclear Spectroscopy Well Logging Sonde. A neutron-capture gamma-ray logging apparatus using a source of fast neutrons surrounded by a bismuth shield to attenuate gamma rays and a detector with a boron shield and an outer bismuth shield to exclude thermal

neutrons and low-energy gamma rays from the detector, and with the sonde case made of aluminum or magnesium to reduce the effect of neutron capture in the sonde case.

U. S. No. 2,956,165. F. F. Johnson. Iss. 10/11/60. App. 6/1/55. Assign. Schlumberger Well Surveying Corp.

Borehole Apparatus. A radioactivity logging apparatus having a detection system with pulse-height discrimination and an auxiliary beta-ray source close to the detector with pulses from the auxiliary source used to control the bias of the pulse-height discriminator to correct for variations in the amplification of the detection system.

U. S. No. 2,956,634. J. Zemanek, Jr. and W. G. Hicks. Iss. 10/18/60. App. 3/14/55. Assign. Socony Mobil Oil Co., Inc.

System for Acoustic Pulse Frequency Logging. An acoustic logging device having a pulsed source and a receiver connected to a pulse-counting system arranged to generate and record a signal proportional to the time interval required for the received wave to complete a predetermined number of oscillations.

U. S. No. 2,956,635. G. C. Summers. Iss. 10/18/60. App. 3/14/55. Assign. Socony Mobil Oil Co., Inc.

Acoustic Pulse Frequency Log. An acoustic logging method in which the source is energized with a pulse having a sharp onset and the frequency of the received wave is measured and indicated as a function of depth.

U. S. No. 2,957,083. S. A. Scherbatskoy. Iss. 10/18/60. App. 6/30/58. Assign. PGAC Development Co.

Radioactivity Well Logging System. A portable radioactivity logging, magnetic casing-collar finder, and casing perforator apparatus employing a single-conductor cable in which amplified pulses from the radioactivity detector are mixed with unidirectional casing-collar signals and the signals separated at the surface and recorded on a two-pen strip chart.

U. S. No. 2,957,159. J. Fitchette. Iss. 10/18/60. App. 2/13/50 and 2/7/55. Assign. Phillips Petroleum Co.

Measuring Device. A system for telemetering bottom-hole pressure and drill vibration to the surface while drilling and in which the pressure transducer varies the carrier frequency of a radio wave that is amplitude modulated by the vibration transducer, the signal being picked up at the surface and indicated, and with a switch on the pressure transducer to turn the transmitter off when pressure is less than a predetermined limit.

U. S. No. 2,957,346. R. F. Knight. Iss. 10/25/60. App. 11/14/57. Assign. Core Laboratories, Inc.

Drilling Rate Measuring Apparatus. A drilling rate recorder having a motor that is energized during drilling and which drives a spring-biased potentiometer whose current is indicated on the recorder, the motor having a clutch that releases after each unit of depth is drilled.

U. S. No. 2,957,990. G. R. Newton and J.E. Skinner. Iss. 10/25/60. App. 1/3/56. Assign. Pan American Petroleum Corp.

Well Formation Density Logging. A gamma-gamma radioactivity logging apparatus having the source and detector in separate housings with a hinged connection between them and a spring to keep them pressed against one side of the borehole, and arranged so that the source-detector distance is fixed at from 15 to 24 inches and the source is maintained less than 2 inches from the borehole wall.

See also Patents 2,951,941; 2,953,686; 2,955,207; and 2,956,162 listed under RADIOACTIVITY PROSPECTING; and Patents 2,951,736; 2,951,738; 2,957,167; and 2,958,010 listed under MISCELLANEOUS.

MISCELLANEOUS

U. S. No. 2,951,736. G. S. Black. Iss. 9/6/60. App. 8/21/58. Assign. Pan American Petroleum Corp.

Variable-Density Recording of Multiple Signal Traces. A system for correcting the light beams of a multi-channel variable-density recorder for variations in zero-signal intensity by interposing in the beam array a negative transparency of the zero-signal pattern.

U. S. No. 2,951,738. R. L. Maneval. Iss. 9/6/60. App. 9/16/59. Assign. Jersey Production Research Co.

Recording Apparatus. A mounting head for the stylus of a multi-channel spark-type recorder in which each stylus is carried in a thin block of plastic having a shoulder abutting a rocker whose angle can be manually adjusted to align the ends of the stylus.

U. S. No. 2,954,608. R. C. Lawlor. Iss. 10/4/60. App. 10/30/56.

Drift and Ground Speed Indicator. An aircraft drift and ground speed meter in which an image of the ground is formed on a phosphorescent screen for a short period controlled by a timed shutter and the length of the streaks measured.

U. S. No. 2,956,434. J. K. Donoghue. Iss. 10/18/60. App. 1/21/54 and 1/17/55. Assign. Simon-Carves Ltd.

Apparatus for Determining Particle Size Distribution. A centrifuge for separating particles of different size suspended in a liquid of lower density than the particles, the inner surface of the centrifuge being stepped and provided with strips on which the particles of different sizes are deposited.

U. S. No. 2,957,167. A. L. Parrack. Iss. 10/18/60. App. 1/8/58. Assign. Texaco Inc.

Method and Apparatus for Speed Variation Compensation in a Recording System. An f-m magnetic recording system in which an auxiliary track with equally spaced impulses is picked up during recording and its signal used to vary the f-m carrier to compensate for speed fluctuations of the recording medium.

U. S. Re. 24,891. (Original No. 2,611,127). W. Palmer. Iss. 10/25/60. App. 10/28/47, 9/16/52, and 7/9/53. Assign. Seismograph Service Corp.

Continuous Wave Navigation System. A c-w radio location system using two channels slightly separated in frequency with the difference frequency used as a long wave-length system, the two carriers being synchronously modulated at lower frequency to provide coarse position indication, the difference-frequency system providing medium position indication, and the high-frequency system providing a fine position indication.

U. S. No. 2,958,010. D. H. Carter and A. E. Nall, Jr. Iss. 10/25/60. App. 4/17/59. Assign. Welex, Inc.

Recording System. A galvanometric reflected-light beam recorder in which the brightness of the light source is controlled from the galvanometer signal and increased in brightness with rate of change of galvanometer current so as to provide uniform photographic exposure of the light beam trace.

SELECTED LIST OF U. S. PATENTS ISSUED DURING SEPTEMBER AND OCTOBER OF 1960

Patent No.	*Subject**	*Patent No.*	*Subject**	*Patent No.*	*Subject*
2,951,291	444	2,952,019[a]	304	2,953,023[a]	180
2,951,359	168	2,952,074	16	2,953,027	16
2,951,365	140	2,952,153	168	2,953,092–093	136
2,951,367[a]	452	2,952,154	16	2,953,214[a]	136, 360
2,951,369	288	2,952,155	200	2,953,303	16, 68
2,951,371	428	2,952,156	288	2,953,312–313	224
2,951,373–378	16	2,952,157	412	2,953,325–329	16
2,951,461	188	2,952,248	148	2,953,505	324
2,951,535	308	2,952,407–408	68	2,953,530	140
2,951,538	36	2,952,416	224	2,953,680	236
2,951,638	68	2,952,424–425	16	2,953,681	148, 308
2,951,639	16, 68	2,952,500	68	2,953,682	496
2,951,652–654	224	2,952,501	324	2,953,685[a]	304
2,951,658	196	2,952,503	224	2,953,686[a]	308
2,951,659	16	2,952,574	40	2,953,687	308
2,951,736[a]	364	2,952,575	196	2,953,742[a]	120, 132, 320
2,951,737	324	2,952,737	224	2,953,785	316
2,951,738[a]	364	2,952,746	224	Re.24,880	16
2,951,912–914	224	2,952,762	196	2,953,858	16
2,951,938	196	2,952,774	308	2,953,925–926	16
2,951,940[a]	252	2,952,777	308	2,953,971	48
2,951,941[a]	304, 308	2,952,806	228	2,953,979[a]	280
2,951,942	308	2,952,812[a]	360, 372	2,954,006	224
2,951,943[a]	304	2,952,833[a]	348	2,954,090[a]	360
2,951,944	308	2,952,834[a]	360	2,954,167	68
2,951,945[a]	304	2,952,844	68	2,954,233	224
2,951,946[a]	304	2,952,845	16	2,954,267–268	324
2,951,982[a]	128	2,952,847	316	2,954,303	224
2,952,000	288	2,952,920[a]	180, 444	2,954,470	236
2,952,006[a]	372	2,953,016	496	2,954,471[a]	144, 148
2,952,010	224	2,953,017	12, 140	2,954,472	308
2,952,012	68	2,953,020	316, 324	2,954,546	224
2,952,014	316	2,952,022	148	2,954,549	68

* A key to the subject classification system will be found in GEOPHYSICS, v. 12, pp. 256–264 (April, 1947)

[a] Abstracted on preceding pages of this issue.

Patent No.	*Subject**
2,954,554	316
2,954,555	312
2,954,608[a]	16
2,954,693	148
2,954,694	200
2,954,939–941	224
2,955,169	224
2,955,170	484
2,955,204	236
2,955,207[a]	308
2,955,208	308
2,955,217	484
2,955,250[a]	128
2,955,251[a]	128
2,955,252	228
2,955,253	228
2,955,277	224
2,955,284–285	316
2,955,459	496
2,955,463[a]	288, 452
2,955,467	224, 288
2,955,470	4
2,955,472–473	16
2,955,474	16, 180
2,955,508	196, 416
2,955,518	444
2,955,533	48
2,955,761–762	68
2,955,781–783	16
2,955,922[a]	252
2,956,162[a]	308
2,956,163[a]	304
2,956,164[a]	308
2,956,165[a]	304
2,956,183	68
2,956,184–185	484
2,956,211	32, 136
2,956,212	484
2,956,224	168
2,956,237	372
2,956,242	368
2,956,251–252	288
2,956,264	468
2,956,271–272	68
2,956,274–275	316
2,956,278	12, 16
2,956,431	412
2,956,434[a]	252, 396
2,956,436	16
2,956,472	444
2,956,576	148
2,956,634[a]	8
2,956,635[a]	8
2,956,636	484
2,956,718	224
2,956,771	236
2,956,789	12, 484
2,956,852	324
2,957,049–051	224
2,957,053–054	484
2,957,074	372
2,957,076	196
2,957,079–081	308
2,957,083[a]	48, 220, 304
2,957,092	12
2,957,096	308
2,957,104	68
2,957,128–129	228
2,957,134	12
2,957,142	12
2,957,153	460
2,957,159[a]	8, 208, 288
2,957,167[a]	224, 364
2,957,171	316
Re. 24,891[a]	312
2,957,338–339	496
2,957,340	140
2,957,341	404
2,957,346[a]	100
2,957,347	200
2,957,350	288, 484
2,957,414	48
2,957,626–627	68
2,957,742	324
2,957,953	224
2,957,954	484
2,957,985	236
2,957,986–989	308
2,957,990[a]	304
2,957,994	484
2,958,010[a]	324
2,958,027	324
2,958,048[a]	372
2,958,056	288, 484

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P. H. DODD received B.S. and M.S. degrees with geology majors in 1947 and 1949 from Northwestern University, Evanston, Illinois. He joined the Raw Materials program of the U. S. Atomic Energy Commission in Grand Junction, Colorado in 1948 as field geologist. U. S. Atomic Energy Commission assignments include research geologist, district geologist, staff geologist, and two years on loan to the Australian government. He currently is Chief of Special Projects Branch of the Production Evaluation Division in Grand Junction.

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W. C. DUESTERHOEFT

JAN GEERTSMA

W. C. DUESTERHOEFT was born in Austin, Texas, December 10, 1921. He attended the University of Texas receiving the BSEE (1943) and the MSEE (1949) degrees and completed studies at the California Institute of Technology where he was awarded the Ph. D. degree in 1953. Mr. Duesterhoeft's experience includes assignments as design engineer for the General Electric Co. from 1943 to 1946 and as aerophysics engineer for Convair 1952 to 1954. He has served as Instructor of Electrical Engineering at the University of Texas and California Institute of Technology from 1946 to 1952, and, since 1954, as Associate Professor of Electrical Engineering at the University of Texas. For the past three years Mr. Duesterhoeft has consulted with Lane Wells Co. on electrical logging problems through the consulting firm Applied Research Associates of Texas, Inc, of Austin, Texas. Mr. Duesterhoeft is a member of Tau Beta Pi, Eta Kappa Nu, Sigma Xi, IRE, and AIEE.

JAN GEERTSMA was born in Holland in 1922. He graduated in 1951 from Delft Technical University with a degree in mechanical engineering after having finished his education in aeronautical engineering at the Haarlem Polytechnic School during World War II. From 1951–1953 he was engaged in research work on the development of new types of flexible mine shafts for the exploitation of deep-buried coal seams in Western-Europe. In 1953 he joined the Oil Production Department of the Koninklijke/Shell-Laboratorium, Amsterdam; he is now a senior research engineer with Koninklijke/Shell Exploratie en Produktie Laboratorium, the Netherlands. He has worked for Shell on various subjects, such as the scaling problem of multiphase fluid flow in porous media and various kinds of problems in rock mechanics. Results of his work have been published in the United States and in Europe.

DIRK C. SMIT

DIRK C. SMIT is a native of Holland. He joined MEKOG, a major fertilizer industry at Ymuiden in 1950, where he worked for 5 years as a research assistant. Since 1955 he has been holding a similar function at the Oil Production Department of the Koninklijke/Shell Exploratie en Produktie Laboratorium, the Netherlands. He followed special training in applied mathematics at the Mathematical Centre in Amsterdam and he is a specialist in programming for digital computers.

JOHN H. HENKEL attended Tulane University from which he received his B.S. and M.S. degrees in Physics in 1947 and 1948, respectively. He was employed by the

JOHN H. HENKEL

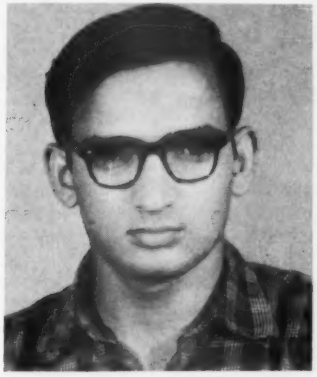
Magnolia Company at their Field Research Laboratories from 1948 to 1951 and from 1954 to 1955. From 1951 to 1954 he attended Brown University from which he received his Ph.D. degree in Physics in 1954. In 1955 he joined the Physics Department staff at the University of Georgia where he is now an Associate Professor of Physics.

During the school year 1959–60 he held a National Science Foundation Science Faculty Fellowship and studied at Princeton University.

Dr. Henkel is a member of the Society of Exploration Geophysicists, Sigma Xi, Sigma Pi Sigma, and the American Institute of Physics.

AMALENDU ROY

AMALENDU ROY was born in 1924. He received his Master's degree in Physics in 1946 from Dacca University, now in East Pakistan. Soon after, he joined the then newly opened Geophysical Section under the Geological Survey of India and was later sent to the Colorado School of Mines where he obtained a Master's degree in Exploration Geophysics in 1952. He joined the Department of Geology and Geophysics at the Indian Institute of Technology (Kharagpur) in 1954, where he received the Ph.D. degree in Exploration Geophysics and is now an Assistant Professor of Geophysics. He is a member of SEG and EAEG.



SUDHIR JAIN

SUDHIR JAIN was born in 1938. He received the B.Sc. Honours degree in Geology & Geophysics and the M. Tech., degree in Exploration Geophysics in 1957 and 1959 respectively from the Indian Institute of Technology (Kharagpur). He is now working with the Oil and Natural Gas Commission, Dehra Dun (India).

J. H. SCOTT

J. H. SCOTT received his B.S. degree, geology major, from Union College, Schenectady, New York in 1951.

After working with Beers and Heroy on a geological research project, he joined the Phillips Petroleum Company to become a seismograph computer. Since 1954 he has been associated with the U. S. Atomic Energy Commission as a geophysicist, first with the Geophysical Research and Development Branch and presently with the Geophysical Services Branch. He is a member of the American Geophysical Union and the Society of Exploration Geophysicists.

P. J. MUDRA received his B.S. degree in Geophysical Engineering from St. Louis University Institute of Technology in 1954. He was then employed by the Atlantic Refining Company, Division of Seismic Exploration, prior to entering the U. S. Air Force. Upon separation from active duty, he joined the U. S. Atomic Energy Commission, Geophysical Research and Development Branch in Denver, Colorado, and is now a member of the Geophysical Services Branch in Grand Junction, Colorado.

P. J. MUDRA

Biographies of the following authors appear in earlier issues of GEOPHYSICS as follows:

F. J. McDonal, v. 23, p. 598; E. R. Niblett, v. 25, p. 1155;

R. L. Sengbush, v. 23, p. 600; K. Whitman, v. 22, p. 735.

MEMBERSHIP APPLICATIONS RECEIVED

Applications for active membership have been received from the following candidates. This publication does not constitute an election but places the names before the membership at large, in accordance with By-laws, Article III, Section 4. References are listed in parentheses following the names of each candidate. If any member has information bearing on the qualifications of these candidates he should send it to the president within thirty days.

APPLICATIONS FOR ACTIVE MEMBERSHIP

Robert H. Adams (R. Maxey Pinson, Lorenz Shock, L. D. Dawson, Nils Lago)

John S. Becker (J. B. Meitzen, R. C. Stone, B. M. Crow, G. O. Morgan)

Oscar A. Buitron (Aart deJong, M. H. Dingman, W. T. Buckingham, R. D. DeJournette)

J. Rowland Cox (D. E. McAnally, J. A. Steacy, J. A. Long, P. S. Stoutjesdyk)

Wilbur E. Dole (R. F. Weichert, F. A. Roberts, T. K. Levy, R. W. Jackson)

S. J. Duda (Dr. A. Schleusener, Theodor Krey)

R. V. Edwards (George O. Morgan, L. A. Markley, J. B. Meitzen, B. M. Crow)

Clarence H. Flowers (R. Maxey Pinson, G. L. Laird, L. J. Waddell, J. E. Clark)

Harry G. Goodin (K. M. Lawrence, J. S. Hopkins, F. F. Campbell, A. I. Innes)

Emery Holzl (P. Sundt, H. Hedstrom, Paul Pelletier, John Cizmark)

Frank T. Ise (R. M. Slinkard, C. W. Hyatt, D. S. Seabrooke, S. C. Stoneham)

Charles H. Layat (Maurice Pieuchot, A. Clement, H. Richard, Bouchon)

Wallace R. Miller (R. C. Clark, Clare N. Hurry, P. M. Tucker, F. L. Lawrence)

Harlo H. Nelson (Hubert Guyod, Verlon Boysen, D. D. Mize, R. N. Ostreim)

Frank W. Schmechel (F. L. Mitchell, S. J. Dallison, J. T. Williams, K. H. Koenen)

James Wafer (E. L. Tomlin, S. R. Marsh, E. J. Laurent, W. E. McCullers)

J. D. Wallis (W. B. Roper, G. W. Isensee, G. B. Davidson, F. P. Troseth)

Jimmy G. Ward (H. K. Richardson, G. E. Tarbox, C. E. Randall, E. A. Grinsley)

Andrew J. Ware (Joe E. Allen, Max Walthall, Leo A Markley, J. B. Meitzen)

Arnold W. West (Thos. P. Maroney, W. C. Calledare, Jr., D. W. Scharf, J. C. Rose)

Robert S. Young (Dr. R. F. Beers, R. S. Edmundson, R. G. Doyle, W. P. Williams)

APPLICATIONS FOR TRANSFER TO ACTIVE MEMBERSHIP

S. T. Algermissen (Kenneth L. Cook, A. J. Eardley, Glenn R. Harris, LeRoy S. Charon)

W. A. Assis (L. A. Martin, J. A. Long, T. B. Portwood, Jr., B. W. Sorge)

F. G. Bryan (F. L. Travis, Jr., S. G. Manos, G. J. Petsoff, H. B. Thomason)

R. L. Burkett, Jr. (J. R. Root, R. E. Gathings, F. H. Agee)

Wm. B. Caro (V. U. Gaither, Byron Vorheis, E. L. Wells)

Thos. H. Crawford (J. R. Ording, D. H. Gardner, H. C. Kriegel, B. F. Ehrlick)

Keith E. Crouse, Jr. (Ross Smith, Jr., W. W. Andrews, C. K. Fielder, L. L. Harp)

John C. Duecker (Dr. T. J. O'Donnell, James Affleck, Sigmund Hammer, R. B. Carter)

Henry E. Engman (G. C. Alvey, R. B. Oldaker, E. B. Manchee, E. E. Pelzer)

Wiley R. Feist (G. O. Morgan, Leo A. Markley, J. B. Meitzen, Homer Wilson)

C. M. Ferree (L. E. Whitehead, Byron Vorheis, E. L. Wells)

Ivan H. Garthwaite (R. W. Aldrich, G. B. Davidson, G. W. Isensee, R. B. Cornell)

Wm. T. Gilland (S. J. Allen, A. S. Maureiro, John C. Hoffman)

James I. Gimlett (D. V. E. Scheid, Prof. J. L. Soske, K. E. Hunter, Wm. C. Kellogg)

Earnest M. Hall (Dave Carlton, W. B. Lee, W. T. Lea, Tom Hall)

John G. Heacock (E. H. Anderson, C. H. Gregory, B. B. Hughson, J. M. Nash)

Andrew Kennedy (H. R. Reuden, R. F. Zimmerly, E. G. Haines, R. D. Holland)

Alton L. Linehan (R. H. Rainey, Ray H. Wright, Sam Evans, Ben Howard)

Paul G. Mathieu (R. E. Dolan, J. N. Wilson, A. J. Barthelmes)

Joseph F. McGlone (Wm. E. N. Doty, K. H. Waters, Graydon L. Brown, Frank Searcy)

Peter M. Randall (H. J. Kidder, M. MacIver, F. E. Halpenny, N. Rothenburg)

Amalendu Roy (P. K. Bhatta Charya, D. K. Gangerly, T. C. Bogchi, S. N. SenGupta)

Daniel Schwartz (T. J. O'Donnell, L. W. Gardner, James Affleck)

Charles E. Schweiger (W. H. Hawkes, Dr. B. A. Tuller, G. L. Ellis)

Edwin R. Scudday (L. F. Uhrig, Leon Fischer, J. W. Rustamier, C. D. Bearden)

Donald W. Smellie (L. W. Morley, J. D. Hobson, L. S. Collett, G. W. Sander)

Edw. R. Smith (R. F. Thyer, K. R. Vale, J. C. Dooley, M. J. Goodspeed)

Richard R. Tharp (James R. Ording, D. H. Gardner, V. L. Redding)

David H. Warren (Eugene E. Cobb, Roy E. Connelly, J. A. Harris, H. E. Stommel)

Jack H. Yelken (W. H. Courtier, H. L. Mendenhall, H. B. Walz, P. M. McNally)

NOMINEES FOR THE 1961–62 EXECUTIVE COMMITTEE

RICHARD BREWER

LAWRENCE Y. FAUST

RICHARD BREWER, candidate for President, was graduated from Purdue University in 1953 with a B.S. in Electrical Engineering. He returned to that institution for graduate work in mathematics and physics, and in 1936 was employed by the Shell Petroleum Corporation as Assistant Seismologist. In 1942, after serving as Seismologist in Louisiana, Texas, and New Mexico, he joined the Electronics Training Group of the U. S. Army Signal Corps, and served in the European and Caribbean Theaters.

In 1946 he joined the Atlantic Refining Company as Assistant District Geophysicist, and his experience with that company included work in South and East Texas, North Louisiana, Arkansas, Mississippi, and Alabama. He resigned in 1954 to become Vice-President of Continental Geophysical Company.

In 1957 he joined C. B. Reed in organizing the consulting firm of Reed and Brewer.

Mr. Brewer has served as President of the Ark-La-Tex Geophysical Society, Vice-President of the Fort Worth Geophysical Society, and has been a member of numerous SEG Committees. He has written several geophysical papers, and is, at present, a Trustee of the SEG Foundation.

LAWRENCE Y. FAUST, candidate for President, served as Editor of the Society from 1957 to 1959, his final issue of GEOPHYSICS being the Silver Anniversary number. Experience in SEG affairs includes Executive Committee membership under Presidents Clifford and McCollum and previous representation to the SEG Council from the Geophysical Society of Tulsa. Formerly he held the first vice-presidency and presidency of the Tulsa section and an associate editorship of GEOPHYSICS.

Dr. Faust's geophysical career began with the Sun Oil Company (1926–1927) primarily in magnetic surveys. This phase occurred between receiving a B.S. from Franklin and Marshall (1925) and a Ph.D. in Physics from University of Pennsylvania (1930). He joined Geophysical Research Corporation in 1930 serving as party chief and later as supervisor. Transferred to the parent company, Amerada Petroleum Corporation, his work has been principally with seismic reflection and refraction methods but has included supervision and interpretation of some gravity and electrical surveys. At present he leads an applied research team; directs geophysical exploration in Somalia for the Sinclair Somal group; directs geophysical exploration in Tunisia for Conorada; and consults with the latter group (Oasis Oil Company of Libya) on seismic interpretation in Libya.

He has contributed papers to GEOPHYSICS, Physical Review, AAPG Bulletin, and Transactions, American Geophysical Union. One of his papers appearing in GEOPHYSICS received the Society's Best Paper Award for 1951. The velocity relationships established in that paper are now frequently accepted as natural laws by other authors in the field.

MILTON B. DOBRIN

MILTON B. DOBRIN, candidate for First Vice-President received the B.S. degree in Physics from the Massachusetts Institute of Technology in 1936, the M.S. in Physics from the University of Pittsburgh in 1941, and the Ph.D. in Geology from Columbia University in 1950. From 1937 to 1942 he was a geophysicist for Gulf Research and Development Company at Pittsburgh and in the field. From 1942 to 1949 he was a physicist at the U. S. Naval Ordnance Laboratory, during which period he participated in the initial atomic bomb tests at Bikini and spent a summer at the Arctic Research Laboratory at Point Barrow, Alaska. On leave from N.O.L. between 1947 to 1949 to complete his graduate studies, he was on the staff of Columbia University as Lecturer in Geology.

From 1949 to 1955 Dr. Dobrin was a senior research technologist at the Magnolia Petroleum Company's (now Socony Mobil's) Field Research Laboratories in Dallas. Since 1955 he has been with Triad Oil Co. Ltd., Calgary, initially as Interpretation Supervisor and since 1960 as Staff Geophysicist. In 1959, he was on special assignment to British Petroleum Co., Triad's parent company, as Geophysical Advisor in Papua, on the island of New Guinea.

Dr. Dobrin was Editor of GEOPHYSICS from 1953 to 1955, having previously been chairman of the SEG's Reviews Committee and the Distinguished Lectures Committee. He was President of the Dallas Geophysical Society in 1953 and the Canadian Society of Exploration Geophysicists in 1960–61. He is currently a member of the Associate Committee on Geodesy and Geophysics of the National Research Council of Canada. He is author of *Introduction to Geophysical Prospecting* (first edition, 1952; second edition, 1960) and has written (as author or co-author) about a dozen papers for geophysical or geological journals.

He is a Fellow of the Geological Society of America and a member of the American Association of Petroleum Geologists, the American Geophysical Union, the European Association of Exploration Geophysicists, the Seismological Society of America, and the Alberta Society of Petroleum Geologists.

H. J. KIDDER

HAROLD J. KIDDER, candidate for First Vice-President was born in Galveston, Texas, and educated through high school in Mexico City, Mexico. He attended Rice Institute, Houston, Texas, and the University of Texas, where he obtained a bachelor of arts degree in physics in 1937.

Upon graduation he joined Geophysical Research Corporation as a geophysical trainee on a seismic crew and worked as geophysical helper and junior computer until 1938, when he was employed by Magnolia Petroleum Company on a company-operated seismic crew. He progressed through all positions to party chief and in 1945 transferred to the parent Company, Socony-Vacuum Oil Company and served in Bogota, Colombia as seismic supervisor until the end of 1947. In 1948 he was transferred to Calgary, Alberta, Canada, as geophysical supervisor and in 1952 became Chief Geophysicist for the Canadian Company, Mobil Oil of Canada, Ltd., the position he now holds.

He is a charter member, past secretary-treasurer, past vice-president and past president of the Canadian Society of Exploration Geophysicists, a past chairman of the Geophysical Committee of the Canadian Petroleum Association, and an active member of the Society of Exploration Geophysicists and the American Association of Petroleum Geologists.

JOHN S. SUMNER, candidate for Vice-President, has been Chief Geophysicist for Phelps Dodge Corporation

JOHN S. SUMNER

in Douglas, Arizona since 1957. He received degrees in physics and geology from the University of Minnesota and a Ph.D. from the University of Wisconsin in 1955. Mr. Sumner served in the U. S. Marine Corps during World War II and in Korea as a fighter pilot. He has been associated with the Cleveland Cliffs Iron Company, Jones and Laughlin Steel Corporation, and McPhar Geophysics, Inc. in his career in mining geophysics.

He is a member of the Society of Exploration Geophysicists, American Institute of Mining and Metallurgical Engineers, the Society of Sigma Xi, and the American Geophysical Union.

STANLEY H. WARD

STANLEY H. WARD, candidate for Vice-President, was born in Vancouver, B. C. He attended the University of Toronto and received a B.S. degree in Engineering Physics, and the M.A. and Ph.D. degrees in Geophysics.

Dr. Ward was Chief Geophysicist and Managing Director for McPhar Geophysics Limited from 1949 to 1954. From 1954 to 1958 he was employed in the same capacity by Nucom Limited. From 1958 to the present he has been a Consulting Geophysicist and since 1959 Dr. Ward has also held the position of Associate Professor of Mineral Exploration at the University of California.

Dr. Ward is a member of SEG, AIME, EAEG, CSEG, AGU, Canadian Institute of Mining and Metallurgy, and Professional Engineers of Province of Ontario.

SAMUEL R. MARSH

SAMUEL R. MARSH, candidate for Secretary-Treasurer, graduated from Baylor University in 1933 with a Bachelor of Arts degree in Physics and Mathematics. During the following two years he was a graduate assistant at the University of Oklahoma where in 1935 he received the Master of Science degree in Physics.

In 1935 he was employed by the Carter Oil Company and for approximately 10 years worked as a seismograph operator and party chief in the southern, midcontinent and Rocky Mountain areas. From 1946 to 1950 he was Geophysical Supervisor for Creole Petroleum Corporation in Venezuela. In 1950 he returned to the United States and has been employed by The Carter Oil Company and Humble Oil & Refining Company as Area Geophysicist with headquarters first in Billings, Montana, but currently in Shreveport, Louisiana.

Mr. Marsh served as president of Montana Geophysical Society in 1956. In 1960 he was general chairman of the Midwestern Exploration Meeting of SEG in Shreveport.

R. MAXEY PINSON, candidate for Secretary-Treasurer, received his higher education at Texas Technological College and Texas Christian University.

R. MAXEY PINSON

JOHN BEMROSE

He joined Texaco in 1947 and was assigned to a refraction seismograph crew. He worked in West Texas and Wyoming until late 1948, when he entered the United States Army. During 1949, he was stationed at Fort Belvoir, Virginia, as an instructor of Photogrammetry in the Engineering School.

Returning to Texaco in 1950, he served on various field seismograph crews and in the Fort Worth Division office until 1953, when he joined Union Oil Company of California as a Geophysicist. Since 1955, he has been Division Geophysicist, with headquarters in Midland, Texas.

In 1958–59, he served as Secretary of the Southern Seismic Well Shooting Association. Mr. Pinson is a past Vice-President, President, and District Representative of the Permian Basin Geophysical Society. He is Co-Chairman of the SEG Membership Committee.

Mr. Pinson is a member of the Society of Exploration Geophysicists, Seismological Society of America, Permian Basin Geophysical Society, West Texas Geological Society, and Sigma Gamma Epsilon.

JOHN BEMROSE, candidate for Editor, is a graduate of the University of London. He took part in torsion balance surveys in England and Iran in 1935 for the International Geophysical Prospecting Company. In 1938 he joined the Royal Dutch Shell group of companies and served as a gravity party chief in Venezuela. In 1940, after a period of training in practical and theoretical seismology in Houston, he served as a seismologist and seismic party chief in South Sumatra, Netherlands, East Indies until the outbreak of the Pacific War. After evacuation to Australia he received a commission in the Royal Australian Air Force and, after technical training, commanded radar stations in Papua and New Guinea. Two years later he returned to Shell in Venezuela as a seismic supervisor and later division geophysicist. In 1947, as chief geophysicist for Shell in the Bahamas, he served on the BAMS coordinating committee in carrying out the largest jointly operated magnetometer survey ever attempted over a marine area. At its conclusion he returned to The Hague to make the basic interpretation of this survey. Late in 1948 he joined Sohio Petroleum Company in Houston, Texas and served for twelve years in various staff capacities in the United States and Canada, and finally as a senior research geophysicist. Recent aspects of his work are involved with the applications of digital computers to geophysical exploration problems. He is presently associated with Sinclair Research Laboratories, Inc., Tulsa, Oklahoma.

He is the co-author of an article in GEOPHYSICS, has presented several technical papers at national and regional meetings of the SEG, served as Chairman of the Distinguished Lectures Committee, and as Secretary, President, and District Representative of the Geophysical Society of Oklahoma City. He is presently Program Chairman of the 14th Annual Midwestern Meeting, scheduled for April 9–11, 1961, in Oklahoma City. He is a member of the Physical Society (London), The American Geophysical Union, the European Association of Exploration Geophysicists, and the Association for Computing Machinery.

R. B. RICE, candidate for Editor, is a native of Oklahoma. He obtained his BA degree in mathematics and physics at the College of Wooster, Wooster, Ohio in 1941. From 1941 to 1945 he taught and did graduate work in mathematics at Ohio State University. From 1945 to 1956 he worked for Phillips Petroleum Company at Bartlesville, Oklahoma, the last ten of these years being devoted to geophysical research. In 1956 he joined the Denver Research Center of The Ohio Oil

Company as Senior Research Mathematician, and in 1960 was appointed Supervisor of the Physics Department.

He has taught graduate courses in mathematics for the Extension Divisions of Oklahoma State University and the University of Colorado, and has published a number of articles on seismic interpretation which have appeared in GEOPHYSICS and various trade journals.

Mr. Rice is a past treasurer of the Geophysical Society of Tulsa and is presently a member of the Research Committee of the Society of Exploration Geophysicists. He is also a member of the Denver Geophysical Society, European Association of Exploration Geophysicists, American Mathematical Society, Mathematical Association of America, American Physical Society, Society for Industrial and Applied Mathematics, Institute of Radio Engineers, and Institute of Management Sciences.

R. B. RICE

ANNOUNCEMENTS

The Officers of the European Association of Exploration Geophysicists for the year ending May 1961 are:

President: B. Baars, Bataafse Internationale Petroleum Maatschappij N.V., 30 Carel van Bylandtlaan, The Hague, The Netherlands.

Vice-President: H. Closs, Bundesanstalt für Bodenforschung, Wiesenstrasse 1, Hanover, Germany.

Secretary-Treasurer: H. J. Hoogeveen, Bataafse Internationale Petroleum Maatschappij N.V., 30 Carel van Bylandtlaan, The Hague, The Netherlands.

Editor: O. Koefoed, Bataafse Internationale Petroleum Maatschappij N.V., 30 Carel van Bylandtlaan, The Hague, The Netherlands.

Past-President: V. Baranov, Compagnie Générale de Géophysique, 50 Rue Fabert, Paris 7, France

CORRECTION

On page 1313 of the December, 1960 issue of Geophysics the fourth and sixth lines state erroneously that Dr. Nelson C. Steenland is the author of the article "Classics of Geophysics" and the editorial "The Silver Anniversary of Geophysics" which appeared in the February issue of Geophysics.

The Editor at that time and the correct author is Dr. L. Y. Faust.

ABSTRACTS

Bulletin (Izvestiya) February, 1960, Academy of Sciences, U.S.S.R., Geophysics Series.

New Principles in Establishing Seismic Regions, Based on an Example from Central Tien-Shan. I

M. V. Gzovsky, V. N. Krestnikov, I. L. Nersessov, and G. I. Reisner

Azimuth-Phase Correlation of Elliptically Polarized Seismic Waves

E. I. Halperin and A. V. Frolova

The theory of the azimuth-phase correlation of elliptically polarized waves is examined. The features of azimuthal seismograms are investigated. Methods are proposed for the solution of the converse problem of finding the wave polarization parameters.

The Frequency Theory of Interference Systems. II

F. M. Holzmann

Theoretical results obtained in Part 1 are used to derive methods for the synthesis of systems in terms of given directional characteristics, and applications of these methods are considered.

On the Application of Seismic Frequency Sounding for the Investigation of the Upper Part of a Cross-Section

T. G. Ivanova

The paper adduces some new experimental data in regard to the variation in the apparent angles of incidence of waves onto the surface of the Earth during the tuning of the apparatus for the registration of various frequencies. It has been established that the angles of incidence of the waves are affected by a soil layer of insignificant thickness.

An interpretation is presented of the dependence of the apparent angle of incidence of a wave on the frequency of the oscillations being recorded, and the velocity in the soil layer, as well as its thickness, have been determined.

Automatic Equipment at the Seismic Stations of the North-Tien-Shan Zone

A. A. Vogel

The paper submits a description of the equipment installed at the seismic stations of the North-Tien-Shan zone intended for the automatic increase of the filament voltage, introduction of multistage scale compression device ("*zagrublenie*"), and a warning system during the recording of earthquakes.

IGY Observations of the Vector of Horizontal Geomagnetic Field Variations

A. G. Kalashnikov and K. Yu. Zybin

Three-component fluxmeter registrations of magnetic field variations are analyzed to determine the behavior of the vector of short-period geomagnetic field variations as a function of the time of day and for comparison with the behavior of the electric field vector. The ratios of the electric to the magnetic components are determined as a function of the period of variation.

Thermal History of the Earth

B. Yu. Levin and S. V. Maeva

Optimum Conditions for Continuous Activation Logging

Yu. P. Bulashevich and S. A. Shulyat'ev

We obtained the distribution of the density of activated atoms along the shaft of a bore with activation by a moving constant or impulse source of neutrons and examined the dependence of this distribution on the rate of logging and the parameters of the medium.

We also obtained an expression for the number of activated atoms and the intensity of the γ-radiation in logging with respect to points. Finally, we cite numerical values for activation effects for bauxite deposits.

On the Theory for Interpreting Gamma-Ray Logs in Layered Media

G. M. Voskoboinikov

We consider a method for calculating the gamma field in a radiating-absorbing layered medium by means of an equivalent transformation into a medium of uniform density. This transformation leads to a general theorem for the area bounded by the gamma-anomaly curve. The theorem can be used to compute the linear reserve of the radiation source in a medium of variable density.

Density and Gravitational Effect of Paleozoic Rocks in the Tatar Republic

A. G. Salikhov and V. P. Stepanov

The authors set forth new information on density variations of Paleozoic rocks in the Tatar ASSR, both laterally and within the Bondyug and Elabuga Devonian structures. They present data concerning the gravitational effect caused by variations of the density interfaces. The given investigations were undertaken in conjunction with detailed gravimetric surveys in the Tatar Republic and adjacent areas.

The Interpretation of Data on the Dispersion of Surface Waves Using Bilogarithmic Grids of Theoretical Dispersion Curves

A. L. Levshin

On the Possibility of the Application of the Multistage Scale Compression Device of Seismographs

V. M. Fremd

Effect of Unilateral Pressure upon Electrical Resistance of Rocks

E. I. Parkhomenko and A. T. Bondarenko

Investigating variations in resistance of rocks under unilateral pressure at various moisture contents, it was established that both the behavior of rocks in a direct electrical current as well as the intensity in variation of specific resistance depend significantly upon the moisture content in rocks. In this connection, the maximum variation in resistance is not observed at maximum or minimum humidity, but at a certain average content of moisture. Apparently such an increase in the conductivity of rocks with pressure occurs as a result of the formation, from liquid, of continuous current-conducting channels upon compression of the sample.

It should also be noted that the most sharp increase in electrical conductivity during unilateral pressure occurs in the range of relatively low mechanical stresses up to 200 kg/cm^2 and the maximum variation, equalling 50–100%, occurred in shales with a moisture content of 28–32%.

The data derived on the variation in electrical conductivity of rocks when exposed to unilateral pressure should be taken into consideration in interpreting the diagrams of electrical logging of deep boreholes.

Calculating the Transitional Resistance of a Cylindrical Grounding in a Bore Hole

I. K. Ovchinnikov

Bulletin (*Izvestiya*) March, 1960, Academy of Sciences, U.S.S.R., Geophysics Series.

New Principles in Establishing Seismic Regions, Based on an Example from Central Tien-Shan. II

M. V. Gzovsky, V. N. Krestnikov, I. L. Nersessov and G. I. Reisner

Travel Times of Longitudinal and Transverse Waves, Calculated From Data on Nuclear Explosions Made in the Region of the Marshall Islands

S. D. Kogan

For the surface focus in the region of the western part of the Pacific Ocean the true travel time of a P-wave is two seconds less, of a PP-wave 5 seconds less, and of a PcP-wave 3 seconds less than that of the Jeffreys-Bullen travel-time curve. In comparison with this same travel-time curve the travel time of transverse waves is 4–5 seconds greater. If corrections for longitudinal waves can be nearly completely explained by the absence of a granite layer in the Pacific Ocean region, then corrections for transverse waves are most likely connected with the fact that the values for the velocity of S-waves in the upper part of the mantle are less than those which are accepted at the present time.

The Seismic Activity of China

Mei Shi-Yun

Methods and Principal Results of Seismic and Gravimetric Studies of the Structure of the Eastern Antarctica

O. G. Sorokhtin, O. K. Kondrat'ev, yu. N. Avsyuk

A brief description is presented of the methods of seismically and gravimetrically determining the thickness of ice under Antarctic conditions. Expediency of a general utilization of these methods is shown. Finally, a cross section is described of the glacial cover along the profile Mirnyi-Pole of Inaccessibility. Some conclusions are drawn as to the geological structure of the East Antarctic mass.

The Energy Consumed in the Formation of the Earth's Crust

E. N. Lustig

In the process of the crust's formation produced by the differentiation of the Earth's mantle, energy of an average order of 10^{26} erg/year is released. If our evaluation of the energy of tectonic processes computed on

the basis of the energy of seismic waves is correct, then, under certain conditions the amount of the released energy may be sufficient for sustaining these processes. From this viewpoint, the most logical scheme would be one based on the assumption that sial rises from the mantle along a planetary fracture.

The Khait Earthquake of 1949 and the Geological Conditions of its Origination

N. N. LEONOV

The Statistically Orthogonal Expansion of Empirical Functions

A. M. OBUKHOV

A method is developed for the statistical analysis of empirical functions that is based on the application of "natural" orthogonal expansions. This method is illustrated by applying it to theoretical models, and also to the analysis of the daily variations of the barometric pressure field with these variations considered as functions of the height. It is shown that in many cases a two-parameter model is sufficiently accurate in describing the pressure variations in the real atmosphere.

An Attempt to Forecast the Time of Near Earthquakes

R. M. KARMALEEVA

Determination of a Refracting Boundary from Azimuthal Station Data

E. V. GLIVENKO

A Detector Unit Incorporating a Photoresistance for Use in Seismic Stations

V. M. FREMD

Sources of Bay-Shaped Disturbances

M. I. PUDOVKIN

Summarizing the results of the conducted analysis of individual bay-like disturbances, one can formulate the following conclusions.

1. Obviously, the source of bay-like magnetic disturbances consists of clouds of elevated ionization, moving at a velocity of about 120 m/sec. The derived relationship of the vector of an excited field with the wind direction in the ionosphere with the normal Earth's magnetic field gives evidence that the dynamo effect constitutes the mechanism of exciting the electric currents in the ionosphere.

2. The electric currents, responsible for the bay-like disturbances, flow in the ionosphere in the form of wide belts (about 400 km wide according to magnetic data and about 600 km wide according to ionospheric data). The height of these currents equals 100–150 km, i.e., corresponds to the height of the *E*-layer. The average current density equals 8×10^{-9} a/cm^2, whence one can conclude that density of electrons in the zone of auroras at the time of bay-like disturbances increases to 10^6-10^8 e/cm^3, which confirms the results of observations on the intensity of aurorae.

One of the Causes of Non-coincidence of Vector of Rock Residual Magnetization with Direction of Magnetizing Field

S. YU. BRODSKAYA AND M. A. GRABOVSKY

1. The vector of residual magnetization in the investigated stratified anisotropic rocks does not coincide with the direction of the magnetizing field.

2. Independently of how the magnetizing field was directed during the onset of magnetic intensity and at present, the vector of the residual magnetization of stratified rock will approach the plane of stratifications. It will remain in almost the same plane upon temporal variation in the field direction, since the longitudinal component always has the predominant value.

3. In the case when the magnetizing field is directed almost perpendicularly to the plane of stratifications, the vectors of residual magnetization of individual samples, remaining almost in the plane of the stratum, may be directed in the opposite direction.

4. The non-coincidence between the vectors I_n and H, caused by the anisotropy of the rock, is stable even in case of magnetization at low temperatures.

The Calculation of a Variable Electromagnetic Field over a Sloping Vein

V. N. NIKITINA

Bulletin (*Izvestiya*) April, 1960, Academy of Science, U.S.S.R., Geophysics Series.

Determination of the Stresses Active in the Foci of Earthquakes, Based on Observations at Seismological Stations

A. V. VVEDENSKAYA

A model of the fault forces, as established by the dislocation theory, is used for studying the stresses effective in the focus prior to the disruption of the continuity of the medium, and which are then released at the moment of the break. A method for determining these directions from the recordings of two or more seismological stations is introduced.

Integral Methods for Interpreting Anomalies ΔZ Having Like Signs

V. N. Strakhov

Integral methods of interpreting magnetic anomalies ΔZ having like signs (i.e., produced by magnetic masses of a like sign) are discussed. Examples of the interpretation of magnetic anomalies of the KMA-type by methods suggested in this article are adduced.

Energy Distribution of Gamma Rays in the Atmospheric Boundary Layer

R. M. Kogan and Sh. D. Friedman

We present calculations of the gamma-ray energy distribution in the atmospheric boundary layer up to a few hundred meters. The calculations were based on a layered-medium model. The radiation sources were radioactive elements of the uranium and thorium series and radioactive potassium uniformly distributed in the top rock layer, or radioactive elements with a given gamma-ray energy E_0 in the form of a thin uniform layer at the rock-atmosphere boundary. The response of some types of isotropic gamma-ray detectors to the gamma-ray field is estimated.

On Determining the Elements of a Seismic Ray from the Data of a Single Station

G. D. Panassenko

An evaluation is given of the errors in determining the azimuthal angle and the coefficient of the horizontal component of the displacement vector for a three-component seismographic setup as a function of the azimuthal angle. It is shown that the probability of these errors in relation to the least error at an azimuthal angle of 45° grows rapidly, as a function of the azimuthal angle. Conditions are given which guarantee a given accuracy in determining the azimuthal angle and the modulus of the horizontal component.

A four-component system for an assembly of seismographs is proposed. Its advantage is shown over the three-component system. Examples of determination of the azimuthal angle and the apparent angle of emergence of a seismic ray from records of a four-component assembly of seismographs of a general type (D. P. Kirnos) at the seismographic station "Apatity" are discussed.

On Certain Results Obtained from the Study of Vertical Gradients of a Magnetic Field in the Area of the Kursk Magnetic Anomaly

M. I. Lapina

Earth's Magnetic Field as the Sum of Fields of Two Dipoles

B. M. Lyakhov

The General Solution of an Axially Symmetrical Problem in Induction Logging Theory

V. N. Nikitina

The Determination of the Anisotropy Coefficient and the Angle of Inclination of a Homogeneous Anisotropic Medium, by Measuring the Impedance of the Natural Electromagnetic Field

D. N. Chetaev

Bulletin (*Izvestiya*) May 1960, Academy of Sciences, U.S.S.R., Geophysics Series.

On the Determination of the Energy of Elastic Waves Generated by Earthquakes

E. F. Savarensky, N. V. Kondorskaya and V. L. Belotelov

The paper examines the question of the determination of the energy of body seismic waves from the data of distant stations, taking into consideration the nonuniformities in the emission by the focus. A device for the evaluation of the density of the energy by the seismogram is suggested. An example is adduced of the determination of the energy of the earthquake of January 3, 1957.

On the Determination of the Energy of Seismic Waves of Arbitrary Form

S. Ya. Kogan

A formula is obtained for the calculation of the energy of Rayleigh surface waves of arbitrary form, using the displacement and the velocity of displacement of the ground at the point of observation. This formula is derived on the basis of a general expression of the density of flow of energy. By way of an example of this general expression, the formula of Zoeppritz-Wiechert for the longitudinal body wave is obtained.

Determination of Pressure in the Vicinity of a Front. 1. The Case of a Liquid Halfspace

A. G. Bagdoev

The penetration of pressure, distributed according to an arbitrary law over the surface of an elastic or liquid halfspace, into the depth of this halfspace is examined. The pressure and stress tensor at the front of a wave in the halfspace are computed. In the case of an inhomogeneous liquid the pressure distribution is computed also in the neighborhood of the front.

The Peculiarities of Seismic Waves in Media with Vertical Interfaces

V. V. KUHN

(From Model Investigations)

This paper describes the results of a study on three-dimensional liquid-solid models of the peculiarities of seismic waves in media with vertical interfaces in the presence of a covering layer. An analysis is made of the dependence of the relative intensity of head and diffracted waves on the thickness of the covering layer and the ratios of the velocities and densities at the vertical boundary. Some examples are adduced of the comparison of the results of the study of media with vertical interfaces obtained both from models and in experimental field work.

Microvariation Station LSU and the Results of its Operation in Borok During the Spring of 1959

B. E. BRUNELLI, O. M. RASPOPOV AND B. M. YANOVSKY

This paper discusses the microvariation station constructed at Leningrad State University for recording short-period oscillations (SPO) of the electromagnetic field of the earth. The advantage of the equipment is presented in comparison with other instruments used for the same purposes. First results are given of the operation of the microvariation station LSU during the Spring of 1959 at the geophysical station of the Acad. Sci. USSR "Borok."

On Vertical Fluctuations of the Water Temperature in the Black Sea

N. T. GLINSKY

Magnetic Anomalous Field of the Tatar ASSR and Its Connection with the Geologic Structure

V. P. STEPANOV

1. All the magnetic anomalies of the Tatar ASSR are connected with the inner structure and petrographic composition of the crystalline basement—with the magnetically active masses within it.

2. Between the depths of occurrence of the basement boundary and the upper edge of the perturbing masses, there was established a fixed dependence, permitting one to determine with sufficient accuracy the depth of the occurrence of the crystalline basement.

3. The banded magnetic anomalies, coinciding with the zones of horizontal gravity gradients, being interpreted as abruptions in the basement, are promising for the prospecting of local structure in the sedimentary layer of the Paleozoic era.

Kazan Geophysical Expedition of the "Tatneftegeofizika" Trust

The Relative Intensity of Head Waves Propagated in Media with Vertical Interfaces

G. N. PARIISKAYA AND V. V. KUHN

The Gravitational Potential of an Elliptic Paraboloid

L. I. GAVRILOV

The Influence of the Earth's Surface on an Electromagnetic Field of Cylindrical Inhomogeneity

B. P. D'YAKONOV

An Application of the Magnetic Modulator and Resonance Amplifier in a Device for the Recording of the Energy Flux of Seismic Waves

A. V. RYKOV

The Dependence of the Zero-Point Drift of Quartz Gravimeters on the Thickness of Fibers of an Elastic System

E. I. POPOV

Bulletin (*Izvestiya*) June, 1960, Academy of Sciences, U.S.S.R., Geophysics Series.

Frequency Theory of the Grouping [*Compositing*] *of Signals on a Background of Correlated Noises*

F. M. HOLZMANN

The principal properties of space-coordinate representations of coherent signals and of non-coherent, correlated noise are examined. Compositing of signals is reduced to filtering of suitable space-coordinate representations. Dependence of the mean-square amplitude of the noise at the output of the group and of the resulting signal-to-noise ratio on the parameters of the group and on the form of the autocorrelation function of the noise are also studied.

Determination of the Depth of the Folded Basement with the Aid of Transmitted Exchange Waves of Type PS Recorded in Earthquakes

N. K. BULIN

The possibility is shown of identifying on seismograms of stations of a general type the transmitted exchange wave, *PS*, which is generated in an earthquake at the surface of the folded basement. Results are presented of the determination of depth of this boundary from seismograms of local and distant earthquakes, registered by the station "Bairam-Ali."

Methods and Apparatus for Airborne Electrical Prospecting

L. Ya. Mizyuk

Various methods of airborne electrical prospecting are discussed. In some of these an electromagnetic field is artificially excited by a source on the ground, in others by a source travelling through the air. The apparatus is described and the various methods are analyzed so as to compare the possibilities they offer for discovering field anomalies caused by variations in the electrical conductivity of rocks. An account of test results is given.

Geomagnetic Charts of Czechoslovakia for the 1958.0 Epoch

J. Bouška, V. Bucha and A. Kočí

Study of a Mixture of Radioactive Elements by Threshold Spectrometers

R. M. Kogan and Sh. D. Friedmann

Certain Regularities in the Behavior of the Vertical Component of Short-Period Variations (SPV) of the Steady Geomagnetic Field (Pc) (based on IGY data)

O. V. Bol'shakova, K. Yu. Zybin and N. F. Mal'tseva

This paper describes certain regularities in the behavior of the vertical component of the short-period variations (SPV) of the geomagnetic field as recorded by he geophysical stations of the Institute of Physics of the Earth, Acad. Sci. USSR, during the first six months of the IGY. Discussed are the SPV field frequency spectrum, the daily variation of the number of SPV cases, the daily variation of the mean maximum amplitude of SPV and their behavior depending on the geographical distribution of the recording points. The term "*Pc* activity" is introduced in order to clarify the general amplitude regularities, and its behavior is discussed.

Determination of Depths and Relief of an Interface by Means of Single Transverse Travel-Time Curves of Refracted Waves

M. M. Radzhabov and L. E. Agranovsky

Selection of Average Velocities in Determining Effective Depths From Single Transverse Travel-Time Curves of Refracted Waves

M. M. Radzhabov

Paleomagnetic Studies of Devonian Sedimentary Layers in the Northwest of the Russian Platform

T. I. Lin'kova

The Direction of Rotation of an Object seen Through a Transforming Optical System

P. F. Shakurov

Determination of Thickness of an Ice Layer by a Radar Method

M. A. Ginsburg

Some Comments on Pochtarev's Paper "The Earth's Magnetic Field in Relation to Other Geophysical Phenomena and to the Geological Structure of the Earth's Crust"

P. N. Kropotkin

On One Attempt to Explain World Magnetic Anomalies

Yu. D. Kalinin

Geophysical Prospecting, Vol. 8, No. 4, Dec. 1960, Official Journal of the European Association of Exploration Geophysicists.

A Shock Wave Theory for the Generation of the Seismic Signal Around a Spherical Shot Hole

W. E. Peet

The shape of the seismic signal generated by an explosive charge is assumed to be governed by shock-wave phenomena in a non-linear region around the shot hole.

The dimensions of this shock-wave region are shown to depend on the weight of the explosive charge and the properties of the medium in which the shot is fired.

The presented theory enables us to elucidate the power law relationship between the amplitude of the seismic pulse and the weight of the charge fired, in the literature often denoted by $A = c \cdot Q^n$, in which A is the pulse amplitude, Q the charge weight and c a constant.

Experiments have been made to check the theory and the results are promising.

Direction Shooting

R. Bortfeld, H. Hürtgen, and H. Köppel

By direction shooting is understood a method of continuous seismic profiling with shots distributed along the total length of the geophone spread, the shots being fired either with time delays in the field, or recorded singly on magnetizable material and composited with time-delays. Therewith, the subsurface can be probed in any desired direction, enhancing reflections from these directions and attenuating or eliminating events from all other directions. For each reflection, the correct delay can be found by a simple procedure from a single trial record.

A complete description of the method is given, inclusive of all procedures and proofs pertaining to it. Synthetic examples and field examples illustrate the efficiency of the method and its resolving power.

Directional Scanning When Playing-Back Seismic Magnetic Records

Karl-Heinz Seelis

In this paper we describe and give examples of procedures of magnetic playback which make it possible to emphasize particular reflections with respect to other reflections of differing step-out. The procedure consists of 100% mixing between non-adjacent channels, using either direct or, more frequently, reversed-polarity mixing signals. This procedure allows the effective separation of differently inclined reflections.

The Influence of Surface Formations on the Apparent Resistivity Values in Electrical Prospecting. 1st Part

L. Alfano

In this first part, we have examined the disturbances on resistivity measurements caused by some simple examples of surface irregularities with a cylindrical structure. The study has been carried out applying a theory developed in a previous paper (Alfano 1959).

In the first place, we have considered the case of measurements carried out with the potential electrodes near the surface irregularities, and the current electrodes more distant from those irregularities. This case is related to those methods of prospecting in which it is preferred to keep the current electrodes fixed and to move the potential electrodes.

One method has been pointed out which will separate, in the measured data, the component of the field due to deep formations, from the components due to surface irregularities. Afterwards, we have considered the case with current electrodes near the dishomogeneities and potential electrodes more distant from them. For both cases, numerical examples are shown, both for secondary charge values and for apparent resistivity values.

Finally, asymptotic values of vertical electrical soundings have been calculated for some cases, rigorously showing that they, in the presence of surface disturbances, are not equal, generally, to the true resistivity of a possible infinite substratum.

It follows that the measurement of resistivity of an infinite substratum, by means of the resistivity asymptotic value of only one sounding, is not possible.

The numerical results given have been obtained by means of calculations based on the abovesaid paper, but whose operative details shall be described in the second part of this paper.

The second part also will deal with the cases of surface dishomogeneity with a noncylindrical structure.

Some Formulae for Interpreting Local Gravity Anomalies

R. A. Smith

Let $Oxyz$ be a system of rectangular axes with origin at the earth's surface and with the z axis pointing vertically downwards. If a body B lies wholly between the planes $z=h$, $z=l$ then for all x, y and for $n=1, 2, 3$ it is proved that

$$\left| D_n(x,\ y,\ d) \right| \leq K\rho d\left[J_n(\alpha) - J_n(\beta)\right]$$

where $\alpha=h/d$, $\beta=l/d$ and K is the gravitational constant. D_n are very easily computed from the Bouger anomaly and J_n are tabulated in this paper.

PERSONAL ITEMS

PRESIDENT KENNEDY has appointed FRANK PRESS to a four-year term on the President's Science Advisory Committee. Dr. Press is Professor of Geophysics at the California Institute of Technology and Director of its Seismological Laboratory.

JOHN E. MASSIE has received a scholarship from the Society of Exploration Geophysicists Foundation, according to MAYNARD W. HARDING, Chairman of Scholarship Administration for the Foundation. Massie is studying at the University of Texas in Geology and Geophysics. He graduated from Sanderson High School, Sanderson, Texas. Massie's scholarship was made possible by a grant from Renwar Oil Corporation of Dallas to the SEG Foundation.

Awards from the Foundation are made as scholarships to outstanding students majoring in fields of interest to petroleum exploration, and as grants-in-aid for teaching and research. The Foundation's trust fund is made up of contributions from organizations and individuals interested in the earth sciences.

Massie, born February 24, 1942 in Gillette, Wyoming is the son of Clifford H. Massie. He was valedictorian of his high school class, a member of the National Honor Society, President of the Senior Class and a letterman in football, basketball and track.

J. D. ISLER resigned his position as Research Section Supervisor for Pan American Research Laboratory in Tulsa in February, to accept a supervisory research position with Lockheed Space and Missiles Division, Palo Alto, California.

WILLIS W. HARDY, assistant to the manager of exploration for Mobil International Oil Company's producing department, retired Dec. 31 after 22 years of service.

Mr. Hardy played a significant role in guiding exploration research at Mobil's Dallas, Tex., field research laboratory, particularly in new geophysical techniques and well logging.

He joined the company as a geophysicist in 1938, and formed the geophysical section. He was promoted to chief geophysicist in 1939. Prior to joining Mobil he was with Standard Oil Company (New Jersey) in Venezuela and Colombia, and with Humble Oil Company in Texas.

Mr. Hardy majored in geology at the University of Chicago. He is a former director of Well Surveys, Inc., and was a member of the American Petroleum Institute's central committee on radio facilities. He is a member of the Society of Exploration Geophysicists and the American Geophysical Union.

The resignation of FRED J. AGNICH and election of ROBERT C. DUNLAP, JR. as a Vice-President of Texas Instruments Incorporated, were announced by President P. E. Haggerty.

Mr. Agnich's resignation was prompted by his desire to devote more attention to his growing cattle ranching and investment interests but for some time he will remain in the employ of the company and continue as a member of the TI Board of Directors.

Mr. Dunlap became operating head of the company's geosciences activities and will continue to serve as President of Geophysical Service Inc., TI's wholly-owned exploration subsidiary.

The TI careers of both men began after their graduation from college and have been devoted exclusively to the company's geophysical exploration or earth sciences activities.

Mr. Agnich joined GSI in 1937 as a helper-permit man with a field crew after receiving a degree in geology at the University of Minnesota. He served successively as party chief and supervisor in domestic and overseas areas and in 1951 was made Executive Vice President of GSI. On January 1, 1956, he became President of GSI and was elected a member of the Board of Directors and Executive Committee of Texas Instruments.

When TI's Geosciences & Instrumentation division was formed in 1959 Mr. Agnich was made its General Manager and a Vice-President of the parent company. At the same time, Mr. Dunlap was elected President of GSI, which was made a part of the new division.

Mr. Agnich has been active in the American Association of Petroleum Geologists, Dallas Geological Society, Dallas Geophysical Society and other professional organizations and has had papers published in the scientific journals of his professional interests. He is a member of the Executive Committee of the Dallas Council on World Affairs, Vice-Chairman of the Aviation Committee of the Dallas Chamber of Commerce, and a member of the American Management Association. He is Chairman of the Board of the Greenhill School in Dallas, a past President of the Dallas Chapter, University of Minnesota Alumni Association, and has served on the Advisory Board of the Dallas Pilot Institute for the Deaf.

Mr. Dunlap is a 1934 honor graduate of Southern Methodist University with degrees in geology and

geography. Before joining GSI he spent a year of graduate study in geology at Harvard.

First joining GSI as a computer with a field crew, he became a party chief in 1937 and supervisor in 1943. He was made a Vice-President of GSI in 1949 and President in 1959. That year he was honored by SMU with the Distinguished Alumni Award in recognition of "significant and demonstrable contributions to humanity and institutional progress."

Mr. Dunlap has served as Secretary-Treasurer and President of the Society of Exploration Geophysicists and as President of the Dallas Geophysical Society. While GSI Vice President in charge of Western United States operations, he served as President of the Pacific Coast Section, Society of Exploration Geophysicists. He also is a member of the American Association of Petroleum Geologists and the Dallas Geological Society.

DR. HARRY J. WERNER, Pan American Petroleum Corp., has been promoted from research group supervisor to research section supervisor. He received his Ph.D. from Syracuse University. Prior to joining Pan American in 1956, he worked as a geological consultant in eastern Canada and as field geologist on the Virginia Geological Survey.

Dr. Werner's teaching experience includes posts at Washington University, Johns Hopkins University and St. Lawrence University. His new duties will involve the supervision of all geological research other than paleontology. He is a native of New York.

PAUL E. MADELEY was elected President of Electrodynamic Instrument Corporation, a subsidiary of Reed Roller Bit Company.

Mr. Madeley, former Executive Vice-President and Engineering Consultant of the expanding electronics firm, succeeds Joseph J. Houghton.

Mr. Madeley is a co-founder of EIC and has had vast experience in research and development work on all phases of seismic exploration equipment and on electronic and electro-mechanical instrumentation for various other industries.

The newly elected president holds several patents covering inventions in the field of electro-mechanical and electronic instrumentation and has many others on application. He is an active member of the I.R.E. and the Society of Exploration Geophysicists.

A native of Conroe, Texas, Mr. Madeley holds a Bachelor of Science degree from the University of Houston. He has previously been associated with Radio Station KPRC where he served as Studio Supervisor, and with Southwestern Industrial Electronics where he worked in seismic exploration equipment design and research for six years.

DARRELL E. SMITH has been named district exploration superintendent of Pan American Petroleum Corporation's Midland district.

Smith joined Pan American in 1948 as a helper on a seismograph party in Wyoming. He has held various geophysical positions throughout the company's Rocky Mountain, Central and Gulf Coast divisions, and also served as senior staff geologist in charge of operations at Casper, Wyoming. Prior to his transfer, he was district exploration superintendent at Shreveport, Louisiana.

A native of Utah, Smith attended high school in Salt Lake City. He did undergraduate work at Kansas State Teachers College and the University of New Mexico, and received his degree in geophysics from the University of Utah in 1949, where he was graduated with honors.

L. C. ADAMS has been appointed manager of exploration for Pan American Petroleum Corp. and will be assigned to the firm's general offices here. The appointment is effective Jan. 1.

Born in New York City, Mr. Adams grew up in Nashville, Tenn., and attended high school at the Montgomery Bell Academy in Nashville. He holds a degree in electrical engineering from the State University of Iowa, where he graduated in 1948.

Hired by Pan American as a junior computer in Houston in February, 1948, Mr. Adams later worked in the firm's Gulf Coast division as a computer, assistant party chief and party chief on seismograph crews.

In October, 1951, he was transferred to Pan Am's Rocky Mountain division in Casper as field seismic supervisor. In May, 1953, he returned again to the Gulf Coast division, as a field seismic supervisor in the New Orleans district and as district geophysicist at New Orleans.

Mr. Adams was appointed district exploration superintendent of Pan Am's Lake Charles, La., district in January, 1955, and he was appointed exploration superintendent for the Rocky Mountain division in June, 1958, the position he will hold until his appointment as manager of exploration becomes effective on Jan. 1.

PHIL H. GARRISON has been appointed division exploration superintendent for Pan American Petroleum Corp.'s Rocky Mountain division, according to an announcement by C. L. Larson, Jr., vice president and division manager.

Mr. Garrison is a native of Golden, Colo., a graduate of Golden High School. He holds a degree in geological engineering with a geophysics minor from the Colorado School of Mines in Golden.

Hired by Pan American in June, 1939, as a recording truck helper on a seismograph crew in Kansas, Mr. Garrison has been assigned at company locations in Texas, Oklahoma, Louisiana and Canada.

He became a surveyor, then a computer and later a seismograph party chief in the firm's Texas-Louisiana Gulf Coast division, Houston, between the years 1940 and 1950. Later in 1950, he was named field seismic supervisor in the North Texas-New Mexico division at Forth Worth.

In June, 1954, Mr. Garrison was appointed division geophysical supervisor for Pan Am's Central division at Oklahoma City, and he held this same position from June, 1955 to March, 1957, at the Company's Canadian division at Calgary.

In March, 1957, Mr. Garrison was appointed geophysical supervisor for the company and assigned to Tulsa. He was in charge of domestic geophysical operations until September, 1959.

Since September, 1959, he has been district exploration superintendent for Pan American's New Orleans district, and he will continue in this position until January 1, when he assumes new duties as Rocky Mountain division exploration superintendent.

Mr. Garrison is a member of the Society of Exploration Geophysicists and the New Orleans Geological Society.

LEWIS R. GRAHAM is now with British-American's South-East Division in New Orleans. Mr. Graham is a graduate of the University of Tennessee. He joined Rayflex Exploration Co. as a computer after graduation. After six years with Rayflex he joined Tidelands to join British-American.

JOHN BEMROSE, formerly a geophysicist for Sohio Petroleum Co., Oklahoma City, has joined Sinclair Research Labs., Inc., Tulsa, Oklahoma, as Senior Research Geophysicist.

LANE HOWELL, formerly with Sohio Petroleum Co., is now employed by Superior Oil Co., as a geophysicist in the Oklahoma District office. He will be doing mostly review work and some current interpretation.

S. BROOKS STEWART, formerly with Sohio Petroleum Co., is now a consultant with an office at 339 Bankers Mortgage Bldg., 708 Main Street, Houston 2, Texas. Mr. Stewart is the District Representative to SEG from Houston.

G. E. "JERRY" FRITTS, formerly in Supervision data processing, Sohio Petroleum Company, has accepted a position with Texaco Inc., Research Laboratories, Bellaire, Texas.

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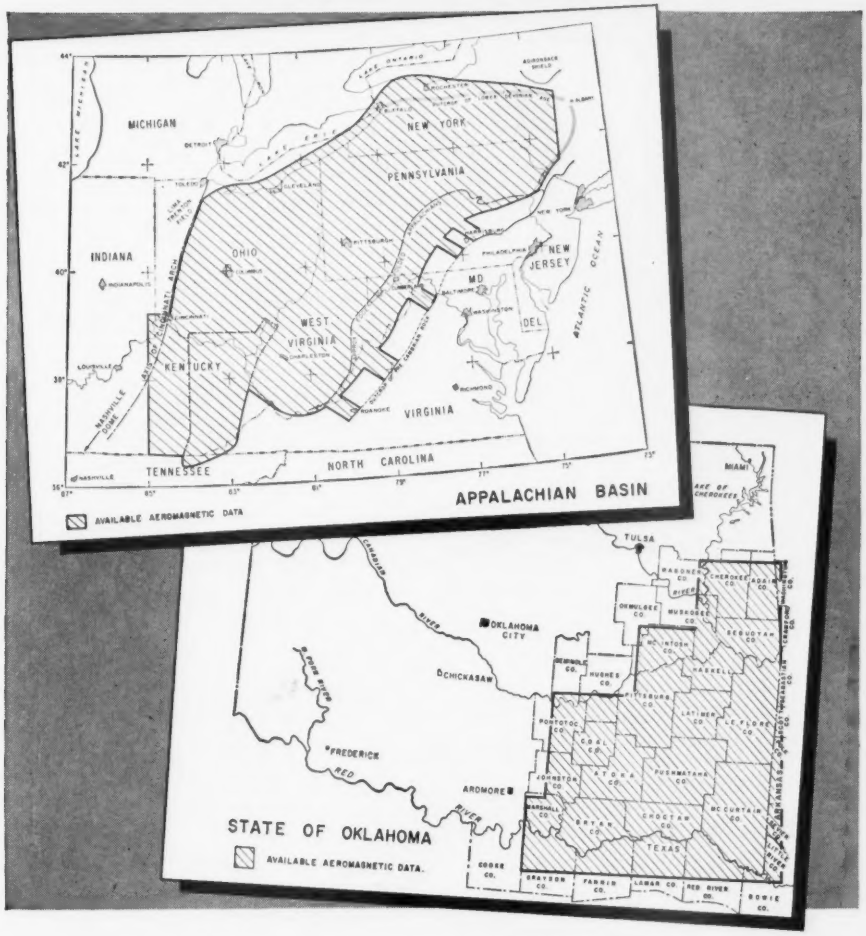

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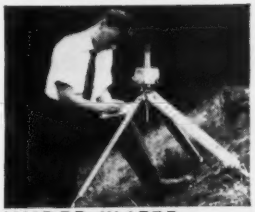

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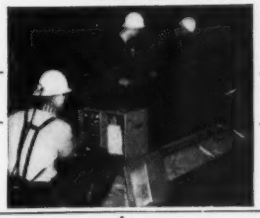

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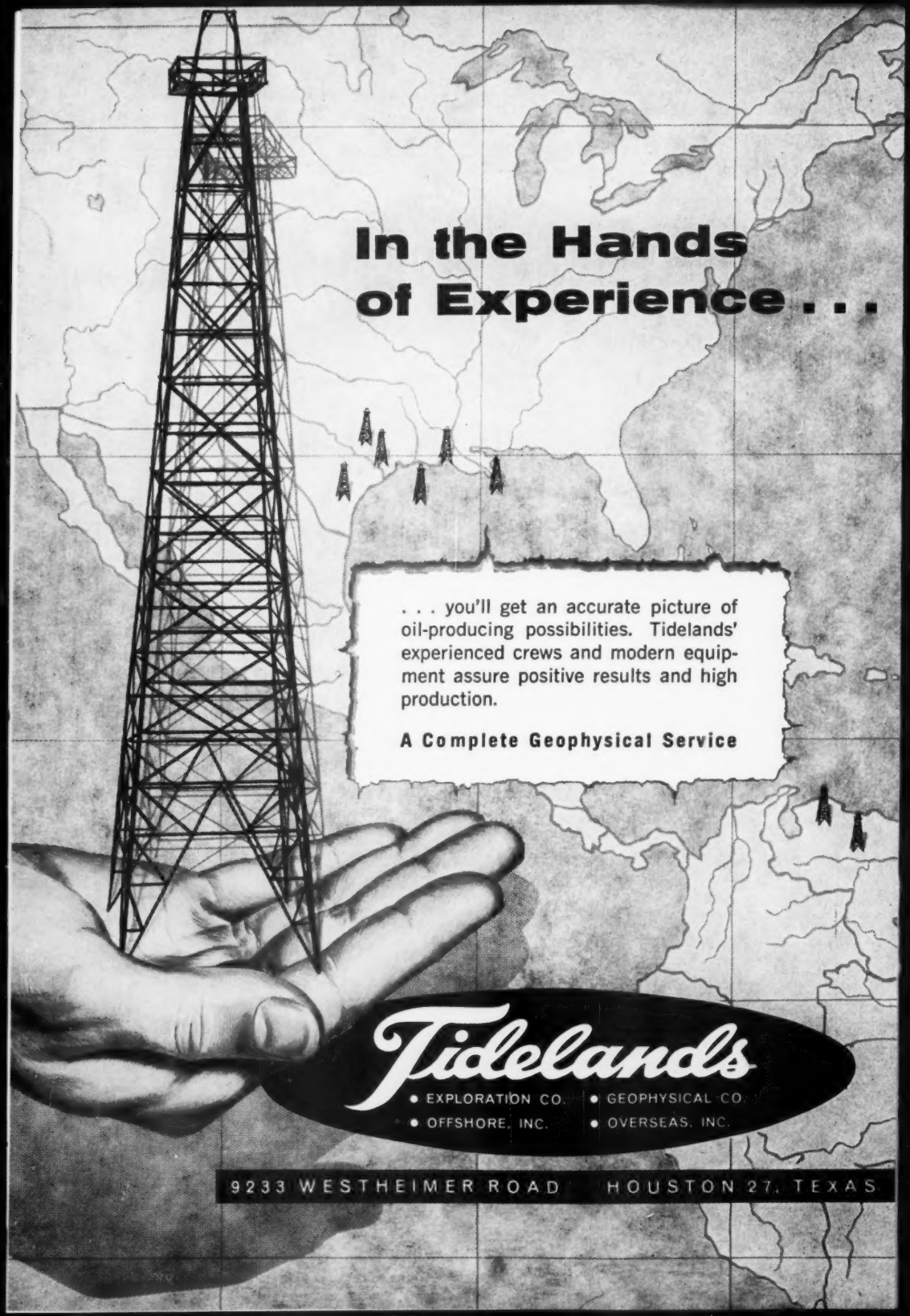
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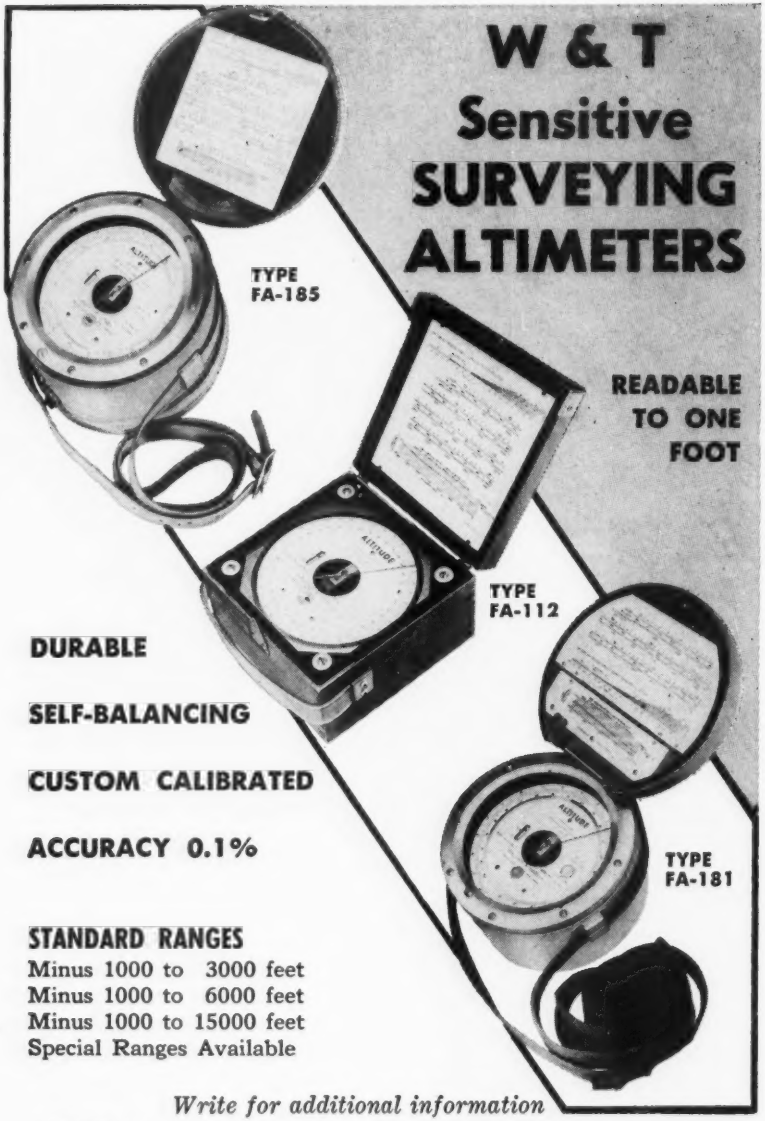

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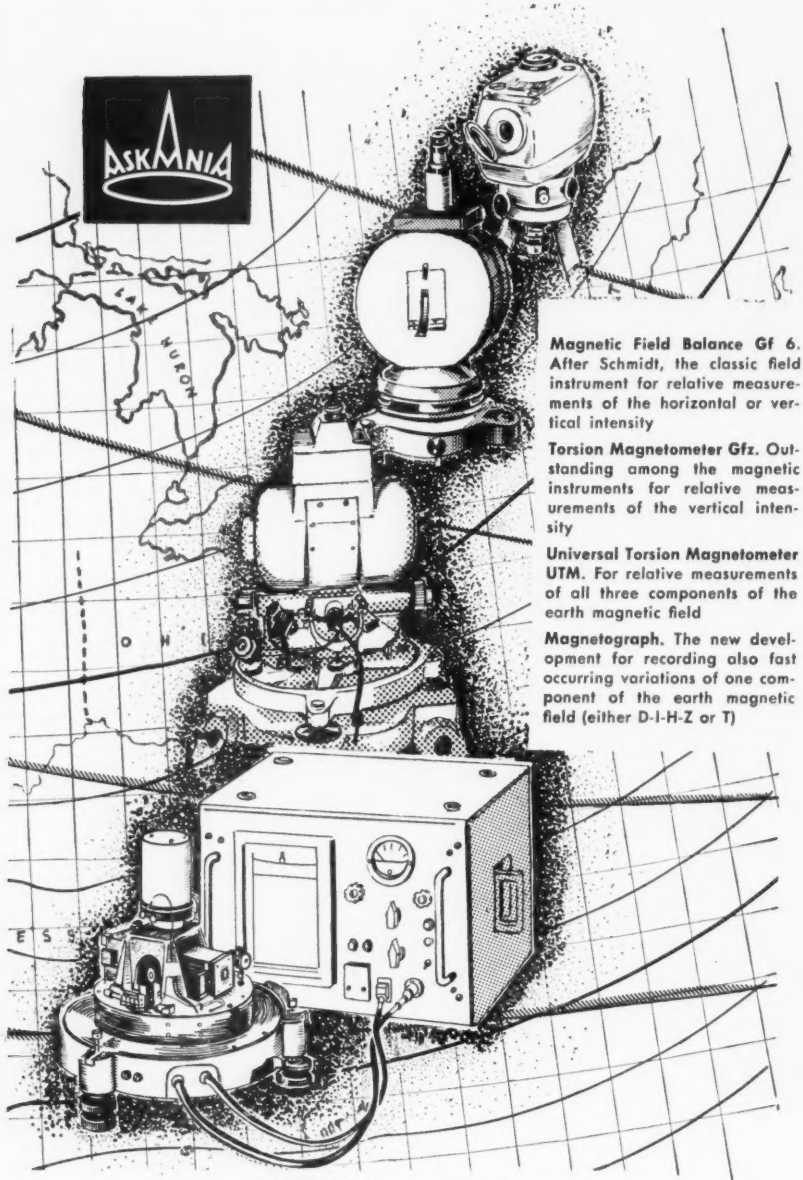

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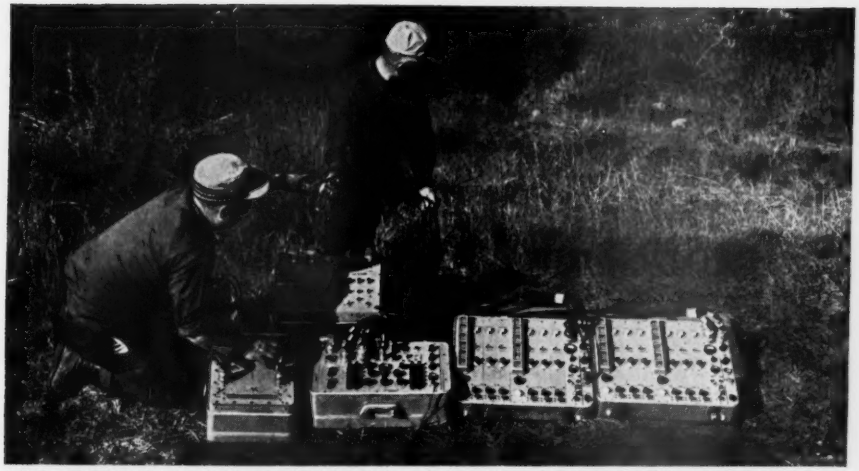

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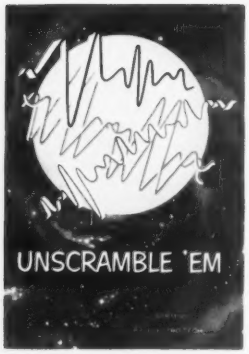

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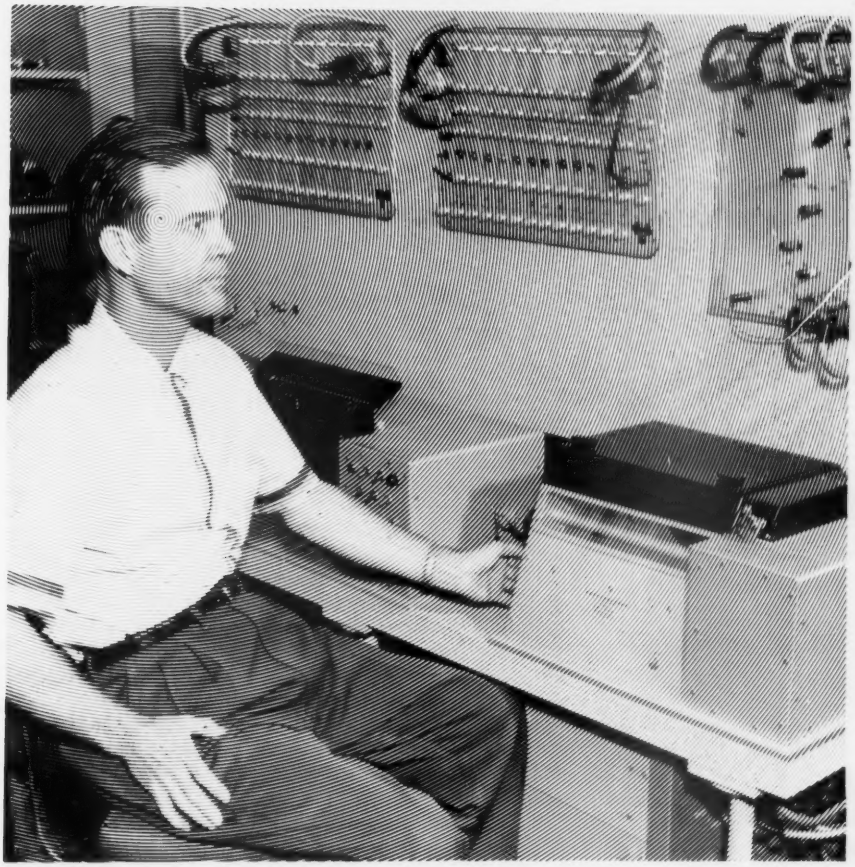

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Petty's research-development laboratories work constantly to develop and improve geophysical techniques. Conception of such advanced techniques as Petty's patented* horizontal stacking process is not enough. Practical implementation of the diverse data handling procedures is also necessary. Accuracy and speed are keynotes of the data processing system developed by Petty to afford economical applications of this technique. From idea to practical application, a method is no better than the thought and attention to detail applied to it. For information write to:

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*U.S. Patent No. 2,732,906

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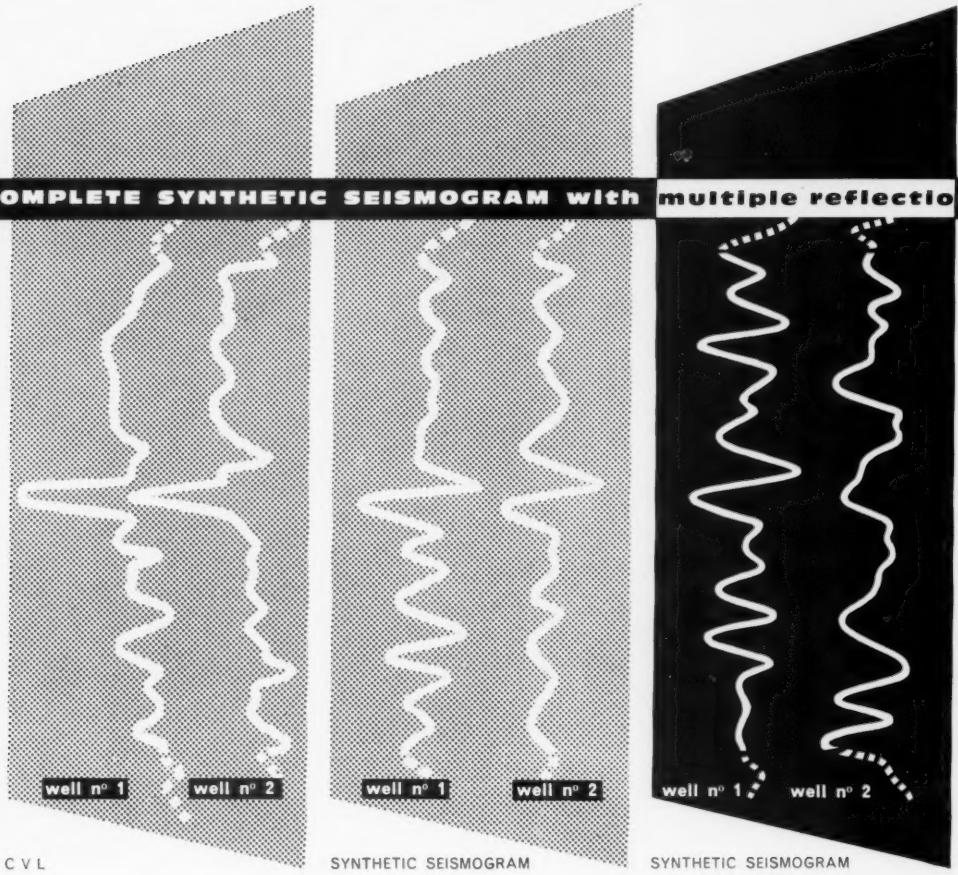

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What geological and geophysical information can be obtained after synthetic seismograms are examined and are compared with the actual records ?

The synthetic seismograms make it possible to ascertain the existence and the quality of the horizons which may be used as good markers

The synthetic seismogram leads to improvements of the field techniques: automatic gain control and filtering

The synthetic seismograms are conducive to a more complete and more acurate interpretation

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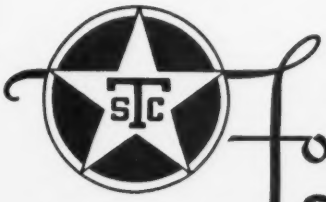

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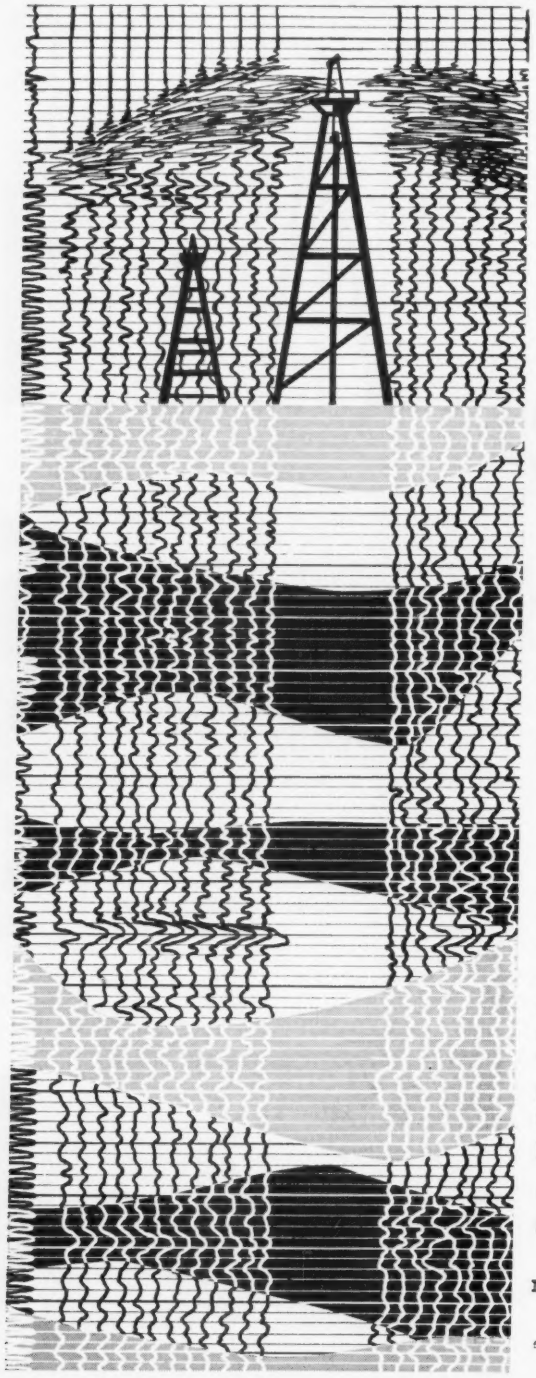

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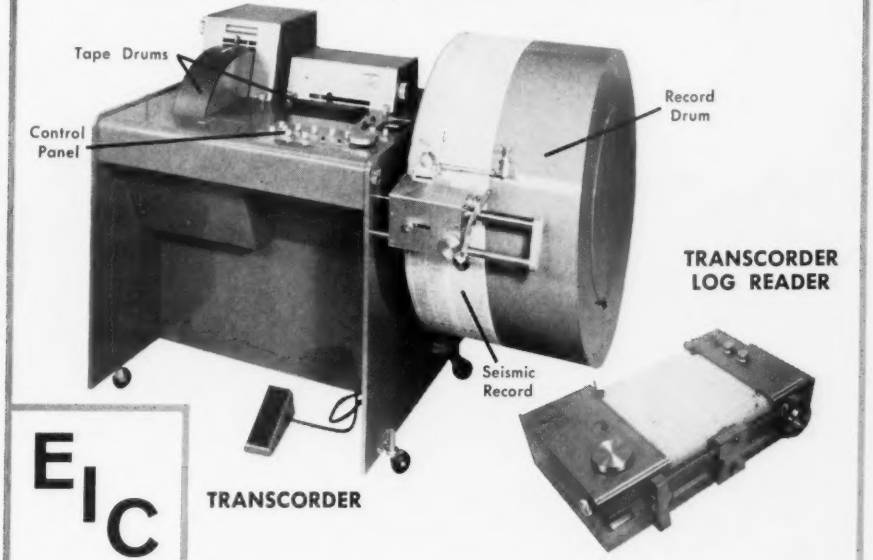
now your tape playback equipment can process data from paper records and well logs

you can often get a more accurate subsurface picture, and thus reduce the likelihood of expensive errors, by transcribing these data onto magnetic tape for processing on a data-reduction system



The Transcorder, EIC's new data-transcribing device, transcribes seismic data onto any standard geophysical tape from paper records, from other sizes of magnetic tape, or, using the Transcorder Log Reader, from well logs. A reproduction of a seismic trace being transcribed can be produced simultaneously for checking purposes.

Magnetic tapes produced by the Transcorder can be processed by playback systems that permit mixing, selective filtering, correcting for moveout, weathering, and elevation, and plotting cross sections by the conventional trace, variable-area, or variable-density methods.

The paper record being transcribed onto tape is mounted on a large revolving drum. The magnetic tape is mounted on another drum that is servo-driven at an infinitely variable rate. The Transcorder will accurately transcribe paper records recorded at speeds ranging from 7.5 to 15 ips. The magnetic recordings produced are accurate within ±1½ ms of the original record at all times.

The Transcorder operator guides the tracking head as the record-carrying drum revolves. (Unskilled office personnel can operate the Transcorder.) The traces are individually transcribed to magnetic tape.

The Transcorder Log Reader, an accessory, permits transcribing well logging data onto magnetic tape in the same manner as conventional seismograms. The resulting tapes can be then converted to cross sections by seismic data reduction systems.

Write or wire EIC for detailed specifications

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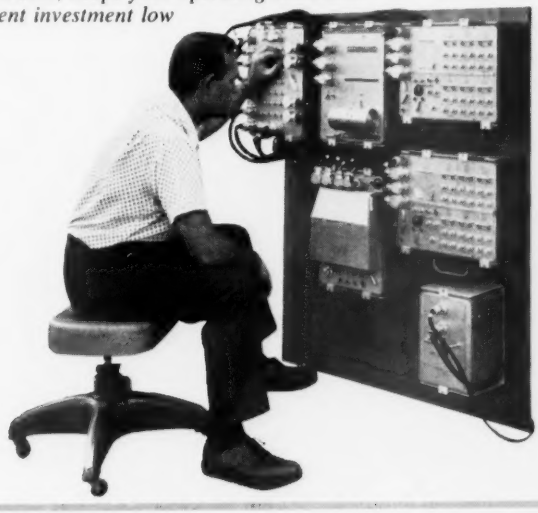
reduce field recording costs with this 157-lb portable seismic system

this complete 24-channel seismic system produces high-quality tape-recorded data, keeps your operating costs and field-equipment investment low



EIC

Although it weighs only 157 lb, the PSS-50 is a complete seismic system, consisting of two 12-channel seismic amplifiers, a tape-transport unit, a translator unit, and a master control unit.

The system's low cost and weight were gained by designing it to utilize fully the capabilities of magnetic tape and by including only needed filtering and display capabilities. The result is a truly portable system that performs superbly.

The seismic amplifiers have a flat frequency response from 8 to 250 cps. Filtering is provided by a separate plug-in unit. Filtering available includes 12 to 24 db per octave slopes, with 20, 30, and 40 cps cutoff points. Cutoff frequencies can easily be changed by plug-in capacitance boards.

A master control unit provides uphole level control, leakage and continuity testing, trip indicator and manual control, trip sensitivity control, master suppression control, avc on-off control, and a test oscillator. Timing accuracy is ± 1 ms.

The tape transport unit has a full 28-channel magnetic recorder, featuring standard EIC door - mounted recording heads. Heads can be interchanged without disassembling the tape transport. Recording heads have excellent low-frequency and transient response. The accurate, reliable drive system uses a hysteresis synchronous motor and a spur-gear transmission.

The translator unit has a playback amplifier with additional avc and filtering control. Traces are displayed on electrosensitive paper by a rectilinear pen writer. Each data channel is played out sequentially and automatically. Timing is provided by preprinted timing lines, with the 100 cps timing trace from the tape played out as a check. Two paper speeds are available, one for a full-length record, the other for expanding the first third of the record (covering the first-break region) over the full paper length. Accuracy from trace to trace is ± 1 ms.

Power required for the PSS-50 is 12 v at 8 a during standby and 18 a while recording.

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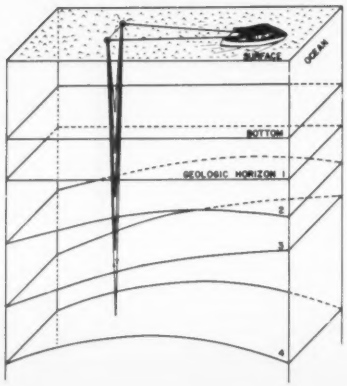

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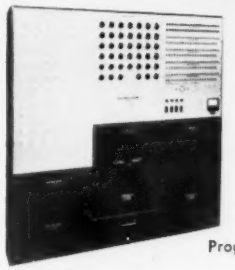
this versatile playback system simplifies your toughest data analysis problems

using EIC's central office seismic data reduction system, you can easily apply precise corrections to field-recorded tapes, use mixing, compositing, or stacking, select the most effective presentation modes

Field Tape Playback Unit

Plotting and Re-record Assembly



Programming Assembly

EIC

C-850

When you own the C-850, you have the most flexible single system available for sequential playback of magnetic tapes. It lets you make maximum static corrections of ±100 ms and dynamic corrections up to 400 ms (at a maximum rate of 500 ms per sec). Timing accuracy is ±1 ms. Any geophone spread length or arrangement can be handled.

During playback, time-corrected seismic data are plotted simultaneously to photographic cross sections. You can choose conventional - trace, variable - area, or variable - density cross sections, or any two of these three. Seismic data can be referenced to any desired datum plane on the cross-section plots. As many as 864 traces can be recorded on a single cross section, which may be as large as 72 x 72 in.

Corrected data are re-recorded during playback for future evaluation. As many as 12 channels of re-recorded tape can be played back for mixing, compositing, or stacking to cross-section plots.

The C-850 can be supplied with any standard-size tape transport. It handles up to 50 seismic and information channels at tape speeds of 7.5, 3.75, or 3.6 ips. It can reproduce direct, FM, or PWM recordings. Re-recording is by FM. Cross-section plotting speed is from 7.5 to 10 ips.

Distortion on FM is less than 1%, on direct magnetic recording, less than 2.5%. Frequency response is from 5 to 500 cps. Signal-to-noise ratio is 52 db (rms-rms) on direct recording, 46 db (rms-rms) on FM.

Such standard EIC design features as door-mounted recording heads and 400-cps hysteresis synchronous motors make the C-850 reliable, easy to maintain, and relatively inexpensive.

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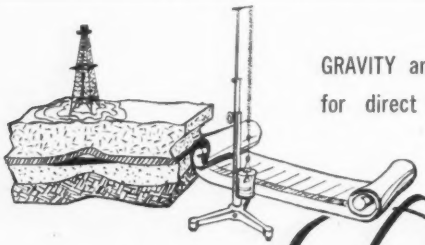

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PB 50/60

Keyboard Input Unit

EIC

The PB-50/60 sequential playback system was engineered and built to give reliable service under adverse field conditions. Its single-console construction makes it easy to move from one location to another, and its rugged, simple construction makes it easy to maintain. Despite its low cost, the PB-50/60 gives you great flexibility of operation and ±1 ms accuracy.

Normal moveout corrections up to 240 ms are available at a maximum rate of 500 ms per sec. Maximum weathering and elevations corrections of ±100 ms can be applied. All corrections are inserted easily and rapidly by a keyboard input unit.

Timing lines on cross sections are recorded directly from field timing signals, giving you accurate trace plots that are in true relation to each other and to record time. Seismic information can be accurately referenced to any desired datum plane. Either conventional-trace or variable - density cross sections are plotted photographically on 24 x 72-in. tape or film. This system can be supplied with any standard-size tape transport.

Modifications of the basic PB-50/60 can be supplied to meet specific requirements.

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fidelity, timing accuracy mark this direct recording magnetic tape system

this direct recording magnetic tape system updates seismic systems to provide high-quality tape-recorded data for analysis in seismic data reduction systems

DR-50

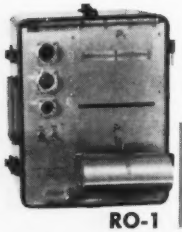
The DR-50 magnetic recording systems produced by EIC record up to 50 seismic and information channels. Record - reproduce heads have excellent low-frequency and transient response. They are mounted on the access door so that they can be inspected, adjusted, or replaced without disturbing the tape transport.

The neatly packaged plug-in amplifiers used as dual-purpose record and reproduce units provide proper playback compensation down to 5 cps.

The DR-50 features timing accuracy of ±1 ms, with trace - to - trace accuracy of ±0.5 ms. Frequency response is from 10 to 500 cps. Signal-to-noise ratio is 52 db (rms). Total harmonic distortion is 2.5%. The DR-50 is driven by EIC's reliable 400-cycle synchronous motor.

The DR-50 is available either with or without a buffer unit. The buffer is used when the seismic amplifier cannot drive the recording heads directly or when a superior signal-to-noise ratio is needed for field playback. EIC engineers are experienced at integrating systems with existing amplifiers and can provide turnkey installation of DR-50 systems.

you get dependable field performance from this rugged recording oscillograph



RO-1

The RO-1 recording oscillograph photographically records up to 28 seismic data traces on 6-in. paper or film. A 400 cps hysteresis synchronous motor provides uniform paper speeds from 3 to 45 ips. Speeds are selected by interchanging easily replaceable drive gears. Precise time correlation is insured by sharply defined timing lines. The RO-1 has 28 pencil-type galvanometers that are available in natural frequencies from 125 to 500 cps. Both galvanometers and front-surfaced mirrors can be adjusted readily in the field. Because the RO-1 produces very little noise in the battery circuit, a single battery can power both the camera and the seismic amplifier. This simplifies battery-charging problems and makes the RO-1 especially suitable for truck mounting.

EIC

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cut uphole shooting time and costs with this precision interval timer

you can obtain weathering and subweathering velocities accurately and efficiently with this interval timer, without using costly seismic recording systems

GT-1

EIC

EIC's GT-1 geophysical interval timer is a precision digital readout instrument that simplifies uphole shooting operations. It provides an immediate visual display of the time interval from shot detonation to the initial seismic wave received by an uphole geophone. Accuracy is ±0.5 ms. A maximum time interval of 255.75 ms can be recorded.

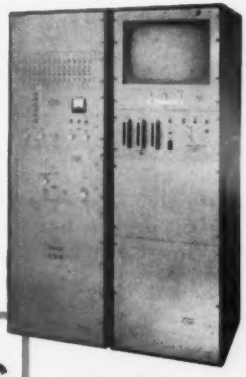
The GT-1 is completely transistorized. It is powered by self-contained dry-cell batteries. The unit's total weight, including batteries, is only 17 lb. Its aluminum carrying case is 16 x 9 x 7¾ in.

now you see results of filtering, stacking, mixing without waiting for cross sections

The MSS-100, a remarkable new multitrace electrostatic storage system developed by EIC, lets you store up to 28 seismic data traces for visual readout on a 17-inch, TV-type, video monitor. This advance in the art of handling seismic data can help you cut the cost of analyzing geophysical data.

The MSS-100 stores data from tape-recorded seismic traces in a special storage tube and displays them continuously on the monitoring tube. Traces can be displayed for as long as 20 minutes without appreciable deterioration. They can be erased instantly to permit storing new data.

Vertical timing lines can be displayed on the video monitor at 1/100-second intervals, with 1/10-second lines accentuated. Either the 1/100- or 1/10-second lines can be omitted if desired.



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MSS-100

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CONDENSED SPECIFICATIONS

Channels: 24 geophysical
4 auxiliary (Time break, up-hole, 100 cps and noise cancelling)

Frequency response: 1 cps to 300 cps within 1 db; 3 db down at 500 cps

Signal-to-noise ratio: 60 db (rms), 1 to 500 cps with noise cancelling.
54 db (rms) 20 to 200 cps without noise cancelling.
(Peak-to-peak noise averages 6-10 db higher than rms noise)

Harmonic distortion: Less than 1%

Crossfeed: Below noise level of recording system

Relative timing accuracy: ± 0.25ms

Power requirement:

	Standby	Operating
Record	2 amp.	7 amp.
Playback	1.5 amp.	6.5 amp.

12 volts D.C.

Dimensions: MR-20 Recorder—8¼"W x 24½"H x 15"D
MU-20 Master Unit—8¼"W x 24½"H x 10½"D

Weight: MR-20 Recorder—60 lbs.
MU-20 Master Unit—45 lbs.

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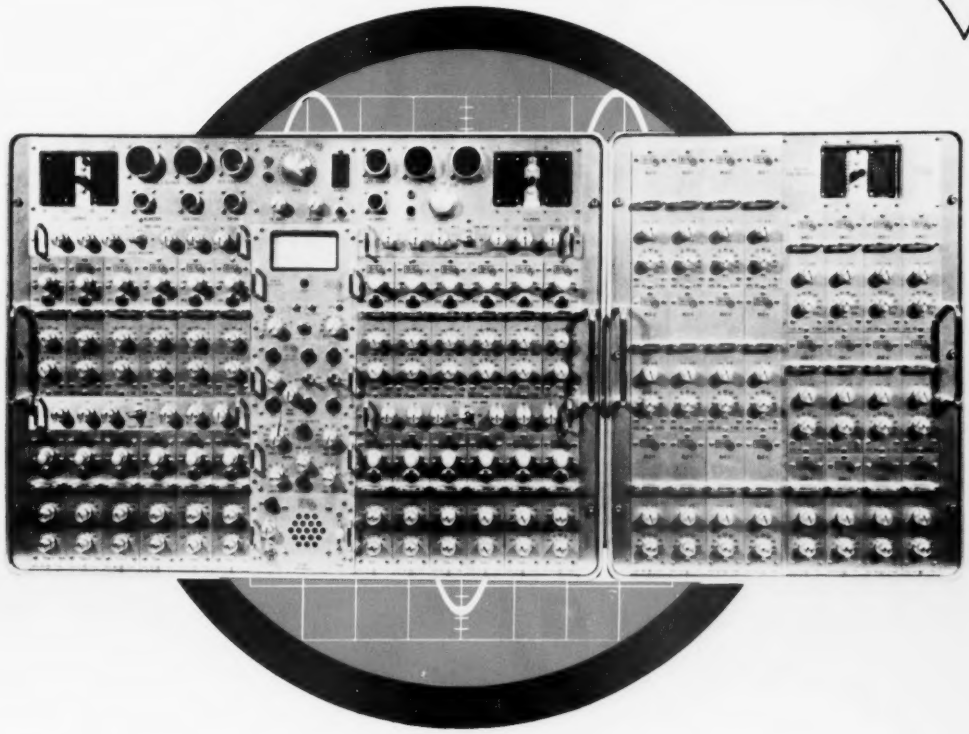
PT-100 Transistorized Seismic Amplifier



SIGNAL CONTROL

With unique light-sensitive photocells as losser elements, the PT-100 eliminates the usual amplifier AGC problems. The critical "diode-balancing" common to other types of AGC circuits is never required. There is no direct electrical coupling between AGC and signal paths to cause distortion and oscillation. Signal voltages do not cause distortion when applied across losser elements as with diode bridge circuits. Drift and temperature instabilities are eliminated. There is a useful operating range of from one microvolt to one volt input — 1,000,000 to 1! Total harmonic distortion under all normal field operating conditions does not exceed 0.5% including heavy reflection standout. External 4 kc signals may be used for programmed-gain operation during amplitude studies. AGC performance down to 5 cps allows use of the PT-100 in refraction work **with AGC control.**

FREQUENCY RESPONSE

The broad band response extends from 3 to 500 cps. Ten logarithmically-spaced cut-off frequencies are provided — from 16 to 135 cps for the low-cut and 23 to 235 cps for the high-cut filter positions. One or two sections (18 or 36 db/octave) may be used.

NOISE

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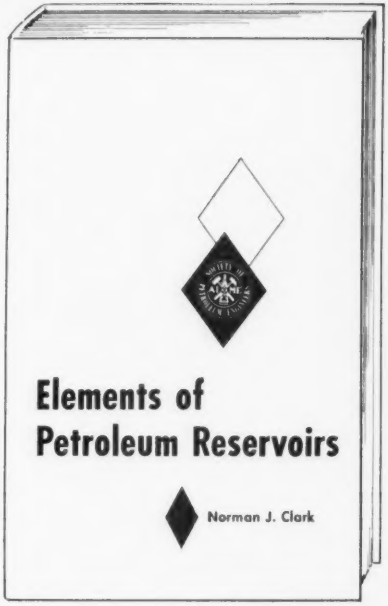

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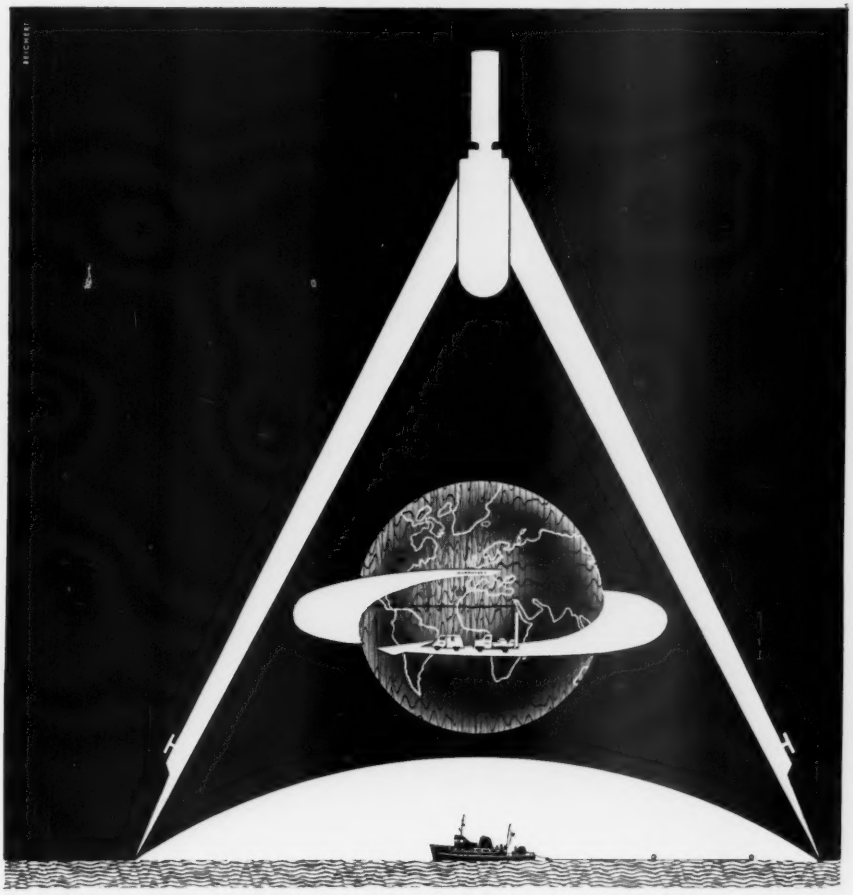

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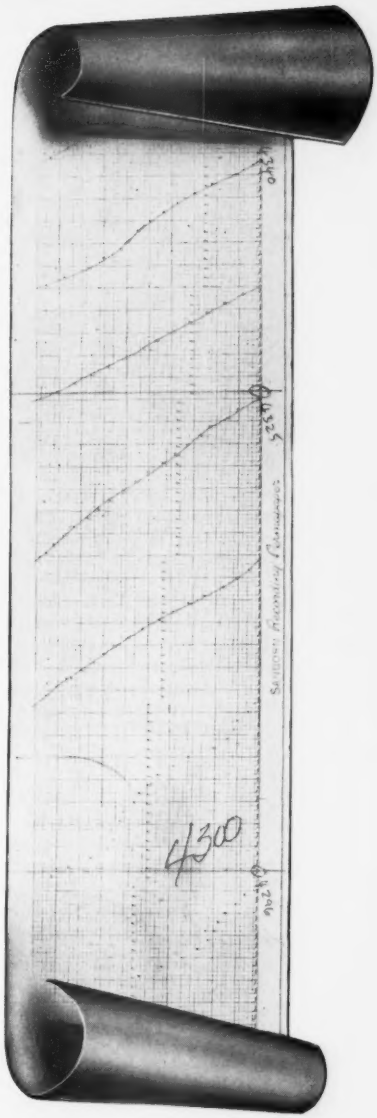

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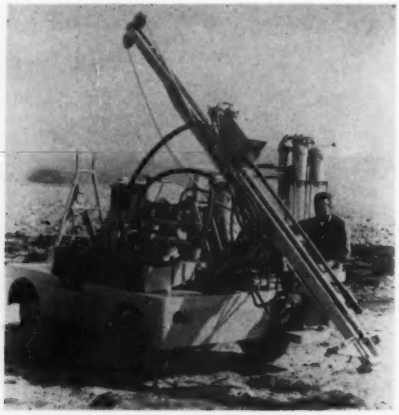

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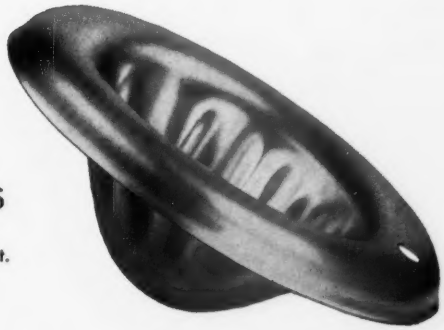

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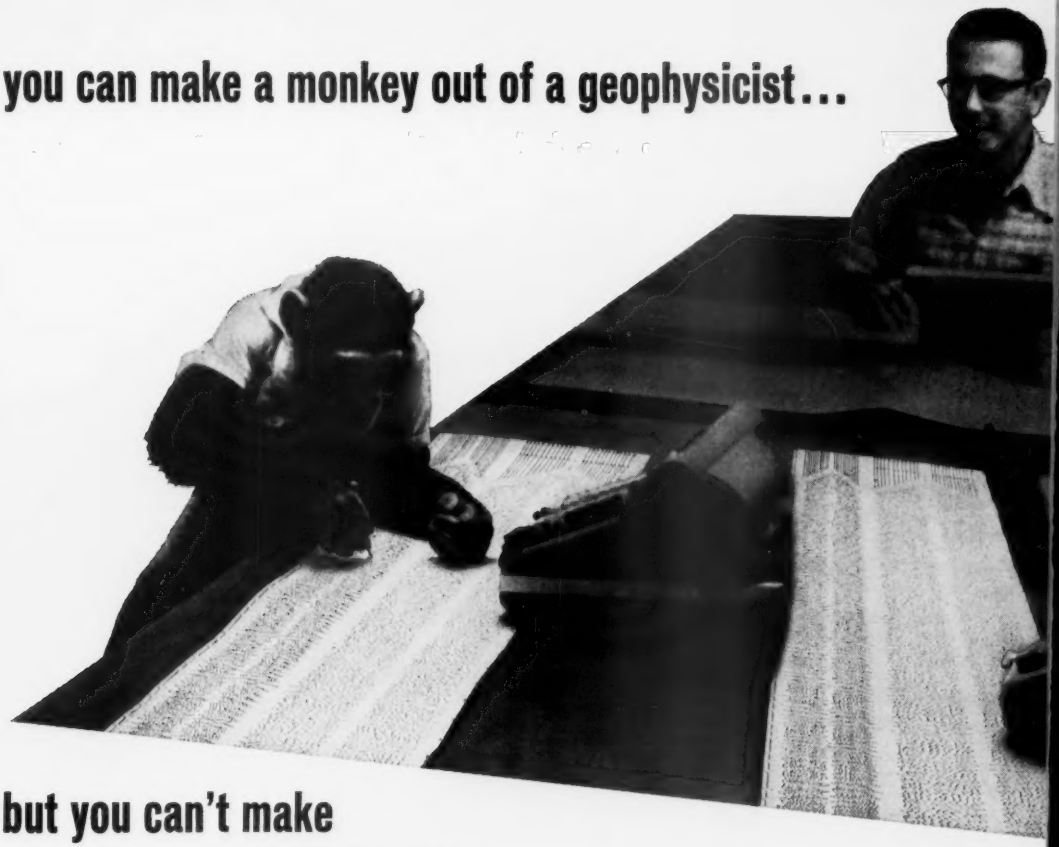

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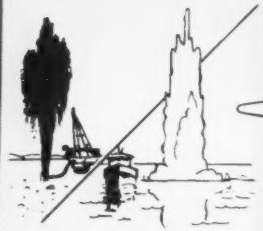

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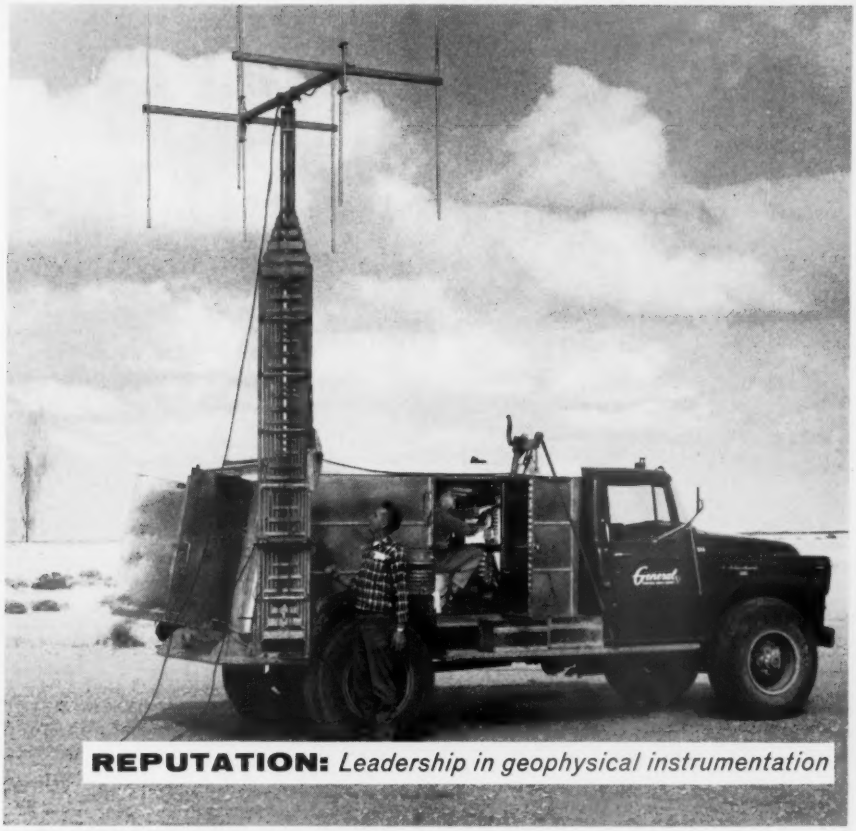

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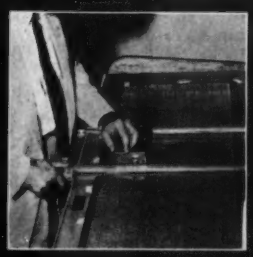

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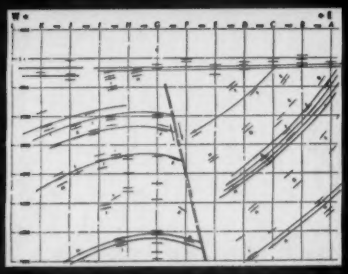

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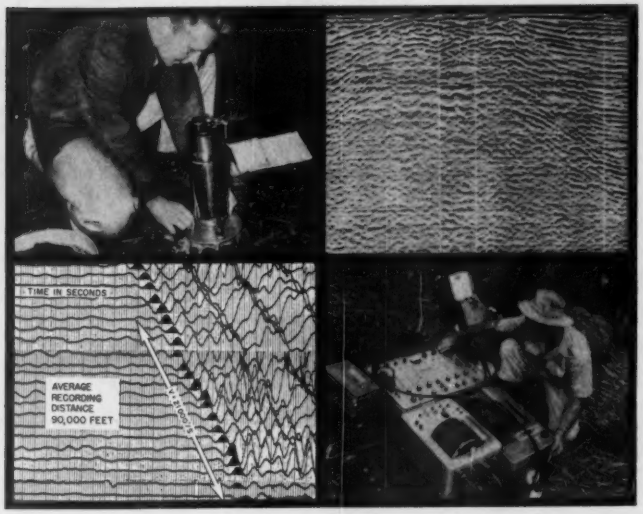

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